Inclined slurry pipelines - solids deposition at shutdowns, pipe blockage and restart

Behnam Pirouz
ATC Williams, Australia
Sadegh Javadi
ATC Williams, Australia
Allan Thomas
Slurry System Engineering, Australia

ABSTRACT

Tailings transport pipelines often include sections of pipe with adverse slopes (such as a pipeline running up the face of an embankment) or horizontal sections with steep slopes at either side (such as a pipeline crossing a bridge over a steep gorge).

The mechanisms involved in solid particles settling in inclined pipelines during the shutdowns are studied in detail using experimental tests carried out with three different size pipes 97mm, 64mm and 25.4mm in a specially developed pipeline blockage apparatus at ATC Williams laboratory facility in Melbourne.

The observations and findings from the experimental testing and analytical methods are utilised to develop a step-by-step procedure for the evaluation of slurry pipeline system performance at shutdowns and system restart process. The developed methodology and recommendations help the designers to improve the reliability and robustness of the design.

SYMBOLS

ρ_m	Slurry density, kg/m^3
C_W	Slurry solids concentration by weight, decimal value or %
C_V	Slurry solids concentration by volume, decimal value or %
SG	Specific gravity of solid particles (relative to water density)
γ_d	Slurry dry unit weight, N/m^3
$\gamma_{d(t)}$	Slurry dry unit weight at time t , N/m^3
γ_w	Unit weight of water, N/m^3
g	Acceleration due to gravity, 9.8 m/s^2
μ	Dynamic viscosity of water 1.002×10^{-3} $(N.S/m^2)$ at 20°C
H	Slurry height at the settling test (m)
H_f	Head loss per known length of pipeline (m of water)
α	Inclination angle of pipe, (degree)
ID	Pipe internal diameter, (m)
D_h	Hydraulic diameter or depth (m)
W_p	Wetted perimeter (m)
T	Top width of the section (m)
σ_e	Effective stress in soil, (N/m^2)
e	Void ratio of soil

1 INTRODUCTION

Depending on the distance and topography of the natural terrain between the processing plant and the tailings Storage Facility (TSF), the longitudinal profile of tailings transport pipelines typically features uphill and downhill sections.

Design and construction of a tailings transport pipeline with only downhill slopes (i.e. positive grade) profile toward the outlet is almost impractical in most sites due to construction constraints and project capital cost. Therefore, tailings pipelines with low points in the profile are unavoidable.

Inclined slurry pipelines can create challenges in the design and operation, especially during shutdown and restart of the system. Low points along the pipeline profile in particular can cause additional difficulties in operation. One of the operational risks associated with inclined slurry pipelines is the risk of solids material deposition at the low points of the pipeline profile at shutdowns which can potentially result in full pipe blockage (i.e plug formation). This risk increases particularly after a power failure shutdown when pipeline flushing and drainage are not possible. The restart of the system in this situation can be problematic.

Different aspects of the design and operation of inclined slurry pipelines have been the subject of numerous studies by different researchers since the 1970s. A summary of some of the research works undertaken before 2010 on inclined slurry pipelines is provided by Wilson et al (1).

One of the earliest research on this topic is the work by Shook et al in 1974 (2). Testing was conducted in an inclined 50 mm diameter pipe and found that for a fully settled bed in a horizontal pipe, angles greater than 22° were required for coarse sand to make the bed slide. The critical slope for fine particle slurry (150 to 0.5 microns) was reported as high as 45°. However, it was observed that solids were transferred to the lower end of the inclined pipe by the natural convective flow process which is called the density current phenomenon. The research concluded that this phenomenon appears to be the cause of the pipeline blockage or plug formation in inclined pipelines at shutdowns. The researchers have also reported that there was very little difference between the concentration profiles measured at the bottom of the inclined pipe whether the pipe was 2 m long or 10 m long. However, they were unable to reach definitive conclusions about the effect of pipe diameter and length.

Further testing with two longer 50 mm diameter inclined pipes were conducted by Shook and McLeod (3). One pipe was 60 m long at 4.43° slope and the other was 30 m long at 7.62° slope. A fine iron ore concentrate slurry (minus 100 microns) at 78% concentration was used in the experiment. The research showed that for longer pipelines and steeper slopes, a longer time is required for the system to reach the final equilibrium condition, but the active length of an inclined slurry pipeline has little effect on the ultimate settled condition at the base of the sloping pipe. They concluded that this situation can be satisfactorily studied by conducting laboratory experiments with short sections of pipe. For short pipes and low inclinations, the time scale of the flow process can be approximated using studies of vertical settling.

Aude and Gandhi (4) reported the findings from testing in a laboratory scale pipe (76mm diameter, 1143mm length and varying slopes between 5% to 45%) as well as a commercial scale operating iron concentrate slurry pipeline (500 mm diameter 400 km long with an average slope of 12.5%). The mechanism of bed formation on the inclined section of the pipeline during shutdown was studied. The study confirmed that the thickness of the settled bed increased along the downslope of the pipe. However, a layer of clear fluid was observed moving near the top of the surface of the pipe at considerable velocity as the solids were settling in the inclined pipe.

Gandhi and Aude (5) reviewed the available research and development for slurry pipeline design in 1978 and identified that limited technical understanding was available on the shutdown and restart process of slurry pipelines with inclined sections. They have stated that further work is required for defining the effect of the pipeline slope and the development of proper slope restriction criteria.

The slurry pipeline blockage mechanisms and challenges at the restart after shutdown with slurry were studied by Shou (6). The blockage situations for three operating slurry pipelines were reviewed in the study and it was recognised that most slurry pipeline blockages are reported during the restart process however, the blockage conditions may have been created during the shutdown with slurry and the blockages are always associated with a sloping pipeline section. The study concluded that the shutdown of a pipeline with slurry normally does not form a complete plug if solids are suspended in the flow before the shutdown. The observations imply that a supernatant layer (water channel) forms at the top of the pipe during the shutdown in most commercial pipelines with a slope less than 30%. To minimise the restart problems, pipeline slopes in long-distance concentrate pipelines are traditionally limited to a maximum slope of about 16%. However, the study suggests that the maximum slope of inclined slurry pipelines should be determined based on not only the slurry settling properties but also the F/f ratio (F- is the available driving force on the plug and f- is the resistance to move). When the F/f ratio is high 30% to 45% slopes may be considered.

The effect of density currents in increasing the slurry solids concentration at the low points of inclined slurry pipelines after a shutdown was studied by Thomas et al in 2002 (7) for two concentrate pipelines; one with an overall average downslope of 1.4% and a maximum 4.7% downslope over a 95 km section (followed by a short section of the pipeline with an adverse slope of about 4%, and the other with an overall average downslope of only 0.047% and a maximum downslope of only 0.15%. The observations in this study showed that for the first pipeline, during a 4 hour shutdown, the slurry concentration in the pipeline increased from an average of 60% to 64% at the low point and reduced to a minimum 54% at the higher point. For the second pipeline after a 10 hour shutdown, the concentration in valley sections increased from an average 37% to 39% and decreased at high points to 33%. The concentration variations at the low and high points of this pipeline have been reported as surprising given the extremely low slopes. It is concluded that the variation has almost certainly occurred because the concentrate was very fine and very slow settling and hence allowing density currents to transfer solids down even very slight slopes.

The effect of pipe inclination angle on the deposition velocity of operating slurry pipelines has also been the subject of several research works. One of the earliest research on this subject is the work by Wilson and Tse in 1984 (8) and a more recent one is the research by Spelay et al in 2014 (9).

Wilson and Tse (8) experimental work was conducted using a 76mm diameter pipe with a varying slope between 0° to 40°. The tested particles were between 1 to 6mm and it was found that deposition velocity in an inclined pipeline could be as much as 50% greater than that measured for a horizontal pipe.

Spelay et al (9) conducted experiments test using 100 mm diameter pipe loop to investigate the effect of pipe inclination (up to 20°) on the deposition velocity of settling slurries. The researchers have reported that for the fine (d~0.1mm) and intermediate solids (d~0.19mm to 0.3mm) the increase in deposition velocity with pipe inclination was marginal. For the coarse solids (2mm and 8mm gravel), the deposition velocity increased significantly with pipe inclination. The research has emphasised that solids particle size and shape play an important role in the relationship between deposition velocity and pipeline inclination. It is also concluded that the database on the subject is still rather limited both in terms of number of data points and the range of pipe diameters tested.

All the evidence from the laboratory testing and operating inclined pipelines indicates that solids are only transferred to low points at shutdowns by the density currents mechanism. The literature review on the inclined slurry pipeline topic also reveals that still a lot of aspects of sloping slurry pipelines especially the behaviour of the system at shutdowns and restarts are unknown and limited knowledge is available on the subject.

The maximum length of the pipeline that can potentially be blocked at shutdowns, the ultimate solids concentration the slurry will reach at the low points of the pipeline profile as time passes after an emergency shutdown, how much time the operators have to flush the pipeline after an unplanned shutdown to prevent a permanent unrecoverable blockage situation, the re-suspendablity of the settled solids in the pipeline and the pumping pressure required to establish the initial flow in a pipeline after a shutdown to un-block the line, re-start the system and clear the settled solids in the pipeline are often challenging questions that the design team has to deal with.

Finding proper answers to these questions is not often easy due to the variability of the slurry properties from one site to another. To improve the understanding of how inclined slurry pipelines behave during shutdown and restart, a series of laboratory experiments have been performed using tailings samples from an operating slurry pipeline. The findings and observations from the laboratory experiments are then integrated with theoretical analysis to develop a step-by-step procedure and recommendations to help the designer to evaluate the pipeline systems that include sloping sections more accurately to identify and address the risks associated with the operation of such systems.

2 EXPERIMENTAL METHOD AND OBSERVATIONS

Mine tailings slurry from an operating Australian lead and zinc mine (tailings system designed by ATC Williams) was used for the experimental part of this research. The measurement of the limiting slope for pipe full blockage was carried out for three different size pipes 97mm, 64mm and 25.4mm. Experimental tests were conducted in ATC Williams laboratory facility in Melbourne using a specially developed pipeline blockage apparatus.

The operating tailings pipeline at the site had an ID = 215mm transporting tailings slurry at an average solids concentration of 33% (by weight) and solids particles Specific Gravity (SG) of 3.04. The Particle Size Distribution (PSD) of solids is presented in Figure 1.

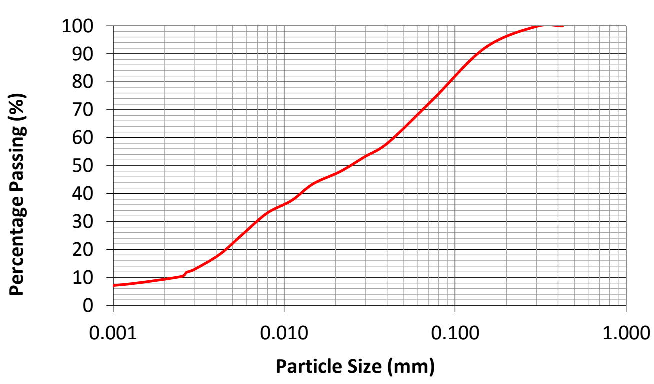

Figure 1 – Slurry particle size distribution

The first set of tests was conducted to simulate the slurry solids particles setting in inclined pipes with different slopes after a shutdown. The tests were carried out in 1m long clear acrylic pipe sections with three different diameters 97mm, 64mm and 25.4mm. To investigate the effect of pipe length on settling behaviour and blockage length, the tests with 97mm and 25.4mm pipes were repeated for 2m long pipe sections. An adjustable slope frame was specifically designed and built to allow the easy variation of the pipe slope to any desired slope for each test.

Each test was started by filling the pipe section with slurry at 33% solids concentration (by weight- the same as the operating pipe on site). The pipe section was initially set at 0° slope (i.e horizontal) and the settled bed profile was measured after allowing the material to settle for 24hr. Then the settled slurry was thoroughly mixed and the pipe was set at 10° slope. After 24hr and recording the settled bed profile, the same procedure was repeated for steeper slopes i.e. 15°, 20°, 25° and 30°. Figures 2 and 3 show examples of the settled bed profiles in 1m and 2m long pipes respectively for 0° and 30° slopes.

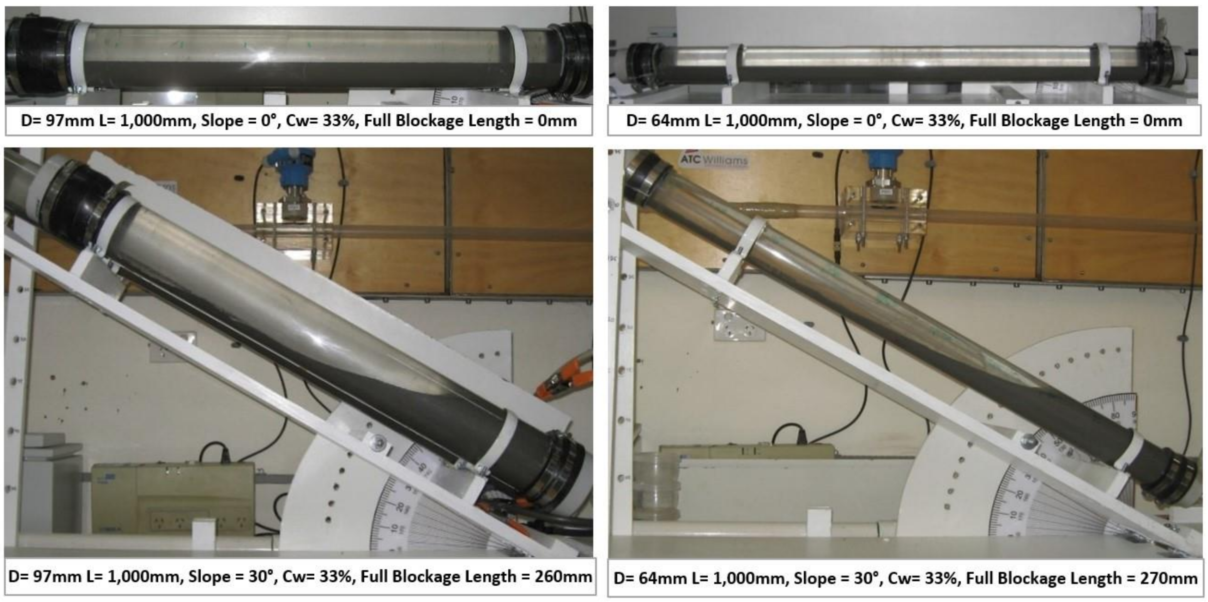

Figure 2 – Settling test in 1m sections of 97mm and 64mm diameter pipes

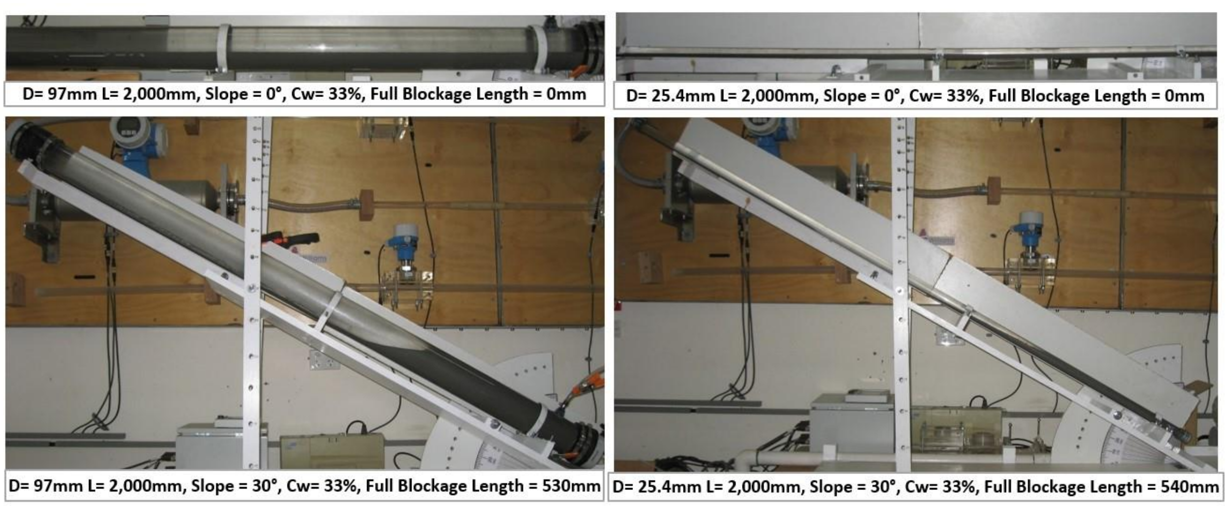

Figure 3 – Settling test in 2m sections of 97mm and 25.4mm diameter pipes

Examples of the settled bed profiles recorded for the experiments with 97mm diameter pipes, 1m and 2m lengths and slopes of 10° and 30° are presented in Figure 4.

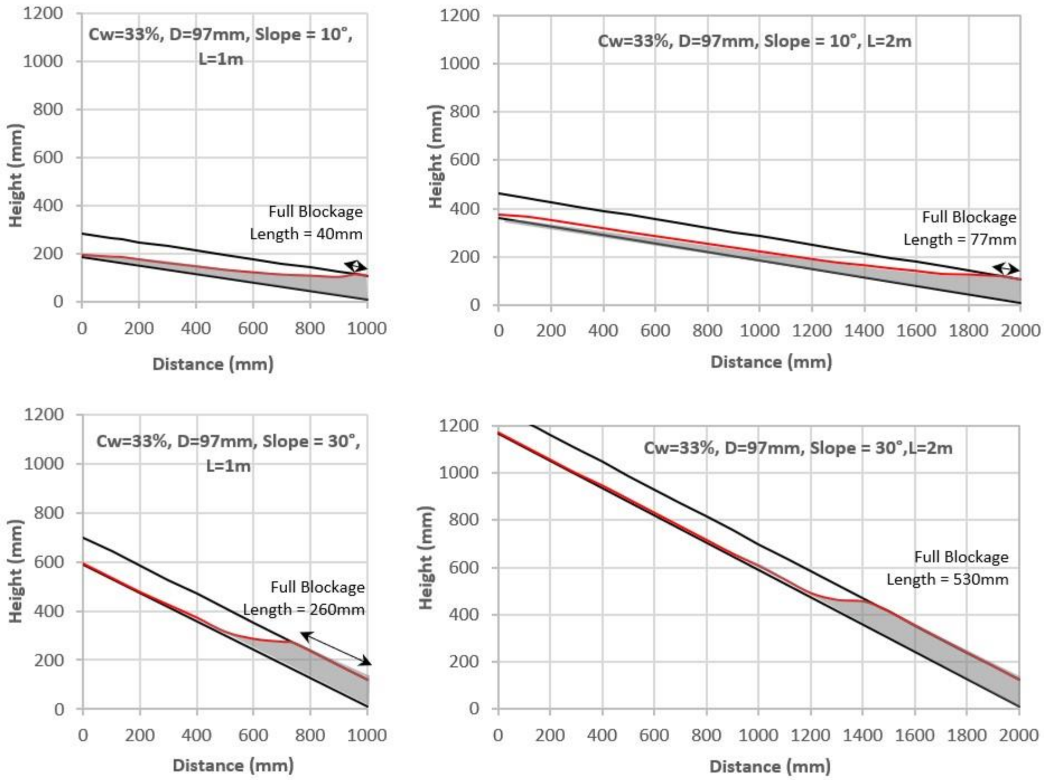

Figure 4 – Examples of the recorded settled bed profiles for 97mm diameter pipe at 10° and 30° slopes (1m and 2m pipe sections)

The observations during the testing with different pipe sizes, slopes and lengths can be summarised as below:

- In the tests performed with the pipes at zero slopes, the material settled evenly to form a reasonably flat and uniform bed of solids with a constant depth of clear water appearing on the top of the settled bed along the pipe length.

- The density current flow by which the solids are transferred to the lower end of the inclined pipe as the material settle, was observed in all slopes steeper than horizontal.

- In the tests with pipes at 5° slope the settled bed forms a gentle profile along the pipe length but the settled solids did not fill the full diameter of the pipes at the lower end of the pipes and a fully blocked pipe section was not observed for any pipe diameter or length even after 24hr.

- In the testing with pipes at inclination slopes between 10° to 30° it was observed that a fast-moving water stream flowing up the slope was established at the top of the pipes while the flow of solids at the bottom of the pipe section moving down the slope formed. The slurry flow at the bottom of the pipe transferred the solids to the lower end of the inclined pipes. This process started as soon as the pipe sections (filled with slurry at $C_w = 33\%$) were placed in the stationary position on the sloping frame. The density current persisted and supplied solids particles toward the lower end of the pipe to replace the upward moving water bleeding off the settled material at the lower end until gradually a certain length of pipe section (starting from the lowest part of the pipe) was entirely filled (i.e fully blocked) with solids.

- Measurement of density profiles with depth was not possible for the settled bed at the fully-blocked section of the pipes, but the visual observations revealed that the materials at the top of the pipe section are looser than the material at the bottom of the pipe.

- The recorded settled bed profiles for pipes with a specific diameter on different slopes show that as the inclination slope becomes steeper more solids materials are transferred to the lower end of the pipe which increases the length of the fully-blocked pipe section. For the 30° slope almost all of the solids in the pipes were transferred to the lower end of the pipe sections with only a few millimetres of solids left at the higher parts of the pipes. This is believed to be due to the fact that the stepper inclination slope provides a longer time for the density current to continue even after the settled bed at the higher parts of the pipe is at a relatively high density.

- The recorded bed profiles also indicate that for the same diameter pipe at any specific slope, an increase in the pipe's length causes a corresponding increase in the length of the fully-blocked pipe section. This is expected as the longer pipe length provides more solid materials that can potentially flow toward the lower end of the pipe.

In the process of fully-blocked pipe section formation, it is expected that as long as the supply of solids particles to the lower end of the pipe continues, the larger pipe diameter should result in a higher average slurry solids concentration as the deeper bed provides higher effective stress for compaction or consolidation of the solids material. This process can be simulated with a series of settling column tests with the aim to estimate the maximum possible solids compaction and expected solids concentration that can potentially form at the low points of a pipeline after a shutdown.

The schematics in Figure 5 illustrate the similarity between the settling of the particles in an inclined pipeline after shutdown and the settling column test.

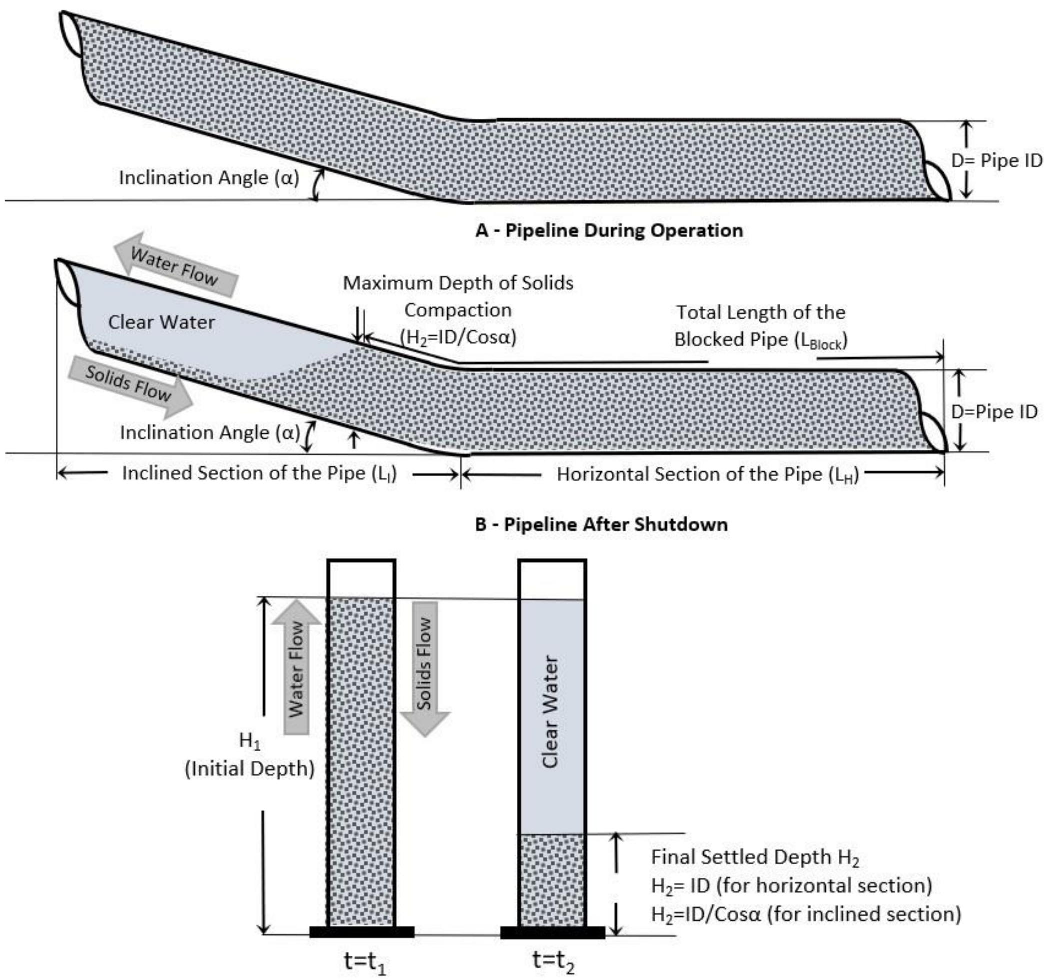

Figure 5 – Solids settling process in an inclined pipeline after shutdown and similarity with settling column test

For a pipe placed at an inclination angle α, the maximum depth of the solids that can form after time t_2 passed from a shutdown can be estimated from Equation (1):

$$H_2 = \frac{ID}{\cos\alpha} \tag{1}$$

From basic geomechanics, we know that the effective stress σ_e, that is applied to the solids particles and compact (or consolidate) the material is independent of the hydrostatic pressure in the pipe and can be estimated from Equation (2):

$$\sigma_e = \left(\frac{SG-1}{1+e}\right) \times \gamma_w \times H_2 \qquad (2)$$

e is the void ratio of soil and is defined as the volume of soil void to the volume of soil solid in a given soil mass.

As it is seen from Equation (2) with an increase in solids depth the effective stress increases and hence the void ratio decreases (which is equivalent to an increase in average solids concentration).

Considering the schematic in Figure 5, if we imagine a settling column test starting with an initial starting solids concentration equal to that of the operating pipeline (i.e. in this case $C_{W(t_1)} = 0.33$ by weight) and an initial starting depth of H_1 which after time t_2 (t_2 is equal to the desired time after the pipeline shutdown) has reached a final settled bed depth of H_2, the average dry density of the settled bed $\gamma_{d(t=t_2)}$ and the slurry solids concentration by weight $C_{W(t_2)}$ can be calculated from the following set of equations:

Dry density of slurry at the start of the test ($t = t_1$):

$$\gamma_{d(t_1)} = \frac{C_{W(t_1)} \times SG}{SG + C_{W(t_1)} - SG \times C_{W(t_1)}} \qquad (3)$$

Dry density of slurry at the end of the test ($t = t_2$):

$$\gamma_{d(t_2)} = \gamma_{d(t_1)} \times \frac{H_1}{H_2} \qquad (4)$$

Slurry solid concentration by weight at the end of the test ($t = t_2$):

$$C_{W(t_2)} = \frac{\gamma_{d\,(t_2)} \times SG}{SG - \gamma_{d\,(t_2)} + SG \times \gamma_{d(t_2)}} \qquad (5)$$

If the final settled bed height (H_2) in a settling column test (started with an initial solids concentration the same as the operating pipeline) is equal to the $(ID/\cos\alpha)$ then the final settled solids concentration at the settling column test is expected to be representative of the maximum solids concentration that the slurry in the fully blocked section of the inclined pipeline can reach during a shutdown.

Figure 6 shows a series of settling column tests that were performed with the slurry sample from the site at starting solids concentration of 33% (by weight) to find the potential maximum solids concentration that the slurry in a fully-blocked section of the pipeline can reach, during pipeline shutdown.

Figure 6 – Settling column test with starting solids concentration at 33% (by weight) and different initial starting depths

The graphs in Figure 7 present the records of the solids-water interface with time in settling column tests. Five tests with an initial slurry solids concentration of 33% (by weight) and initial slurry depths of 171mm, 203mm, 256mm, 304mm and 580mm were conducted. As seen in Figure 7 when the settling curves of the four tests are normalised to the initial depths, the five settling curves collapse on each other representing the settling behaviour of the slurry.

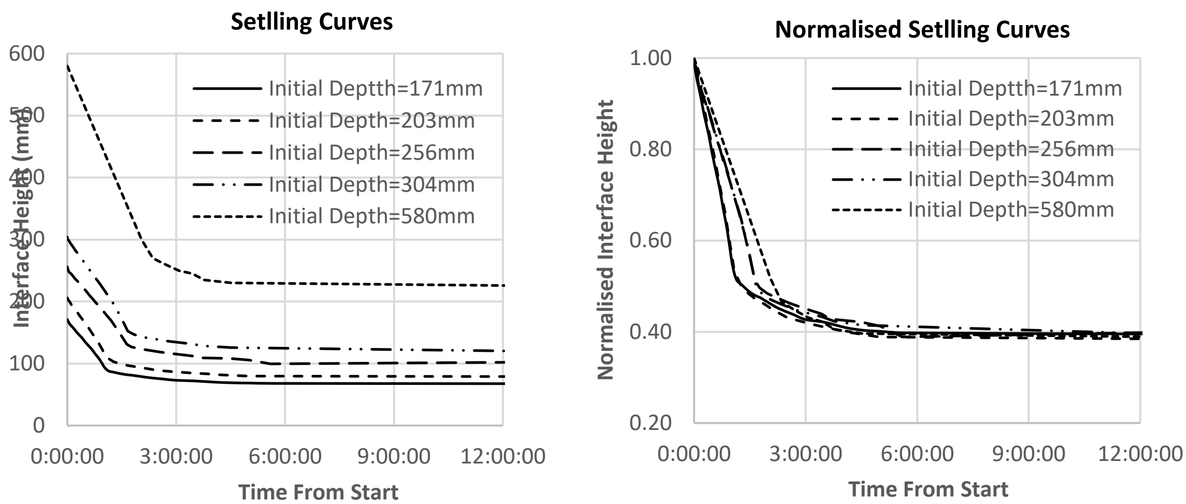

Figure 7 – Settling curves from column test with starting solids concentration at 33% (by weight) and different initial starting depths

3 ANALYSIS

The settling curves in Figure 7 and Equations (3), (4) and (5) can be used to generate a set of plots similar to the ones presented in Figure 8. The first graph in Figure 8 shows the final settled bed height versus the initial starting slurry depth while the second and third graphs represent the final achieved settled solids concentrations (by weight and also by volume) versus the initial starting depth and the final settled depth (after 24hr) respectively. Using this set of graphs, the expected maximum solids concentration in a fully blocked section of the inclined pipeline on site can be estimated by selecting a final settled bed depth equal to the site pipe $ID/\cos\alpha$. It should be noted that this estimation is only valid if the pipeline inclination slope is steep enough for the formation of a full-blockage pipe section.

Based on the schematics presented in Figure 5, if a pipeline includes a horizontal section with a length H_L and an inclined section with a length of H_I, the maximum length of the pipeline that can potentially be fully blocked after a shutdown can be calculated by equating the volume of slurry in the pipeline before and after a shutdown. It should be noted that to estimate the maximum blockage length, it is assumed that all of the solids in the inclined section of the pipeline will be transported to the low points of the pipeline profile by the density current. This assumption is only correct if the pipeline inclination angle is steep enough.

$$L_{Blockage(Max)} = \frac{C_{V(t1)}}{C_{V(t2)}} \times (L_I + L_H) \tag{6}$$

$$L_{Blockage(Max)} = \frac{C_{W(t1)} \times \rho_{m(t1)}}{C_{W(t2)} \times \rho_{m(t2)}} \times (L_I + L_H) \tag{7}$$

$$\rho_m = \frac{1}{(C_W/SG) + (1 - C_W)} \tag{8}$$

If the analysis is being performed for an inclined pipe section only with no horizontal pipe section (like the test conducted in this research) then $L_H = 0$.

As demonstrated in Figure 8 for the pipeline under study in this research, (ID=215mm and the pipe inclination angle of $10°$) the final settled bed is equal to 218mm and the corresponding expected final solids concentration is 64.4% (by weight).

In the first graph of Figure 8, the estimated final settled bed heights for the pipe diameters used in the experimental tests of this research are plotted for the pipe inclination angle of $10°$. These values are used in the second and third graphs of Figure 8 to estimate the final solids concentrations in the fully blocked sections of the tested pipelines after 24hr.

Equations (6), (7) and (8) together with the final solids concentration values obtained from Figure 8 for the tested pipes are used to estimate the maximum lengths of pipes that can potentially be fully blocked in each test.

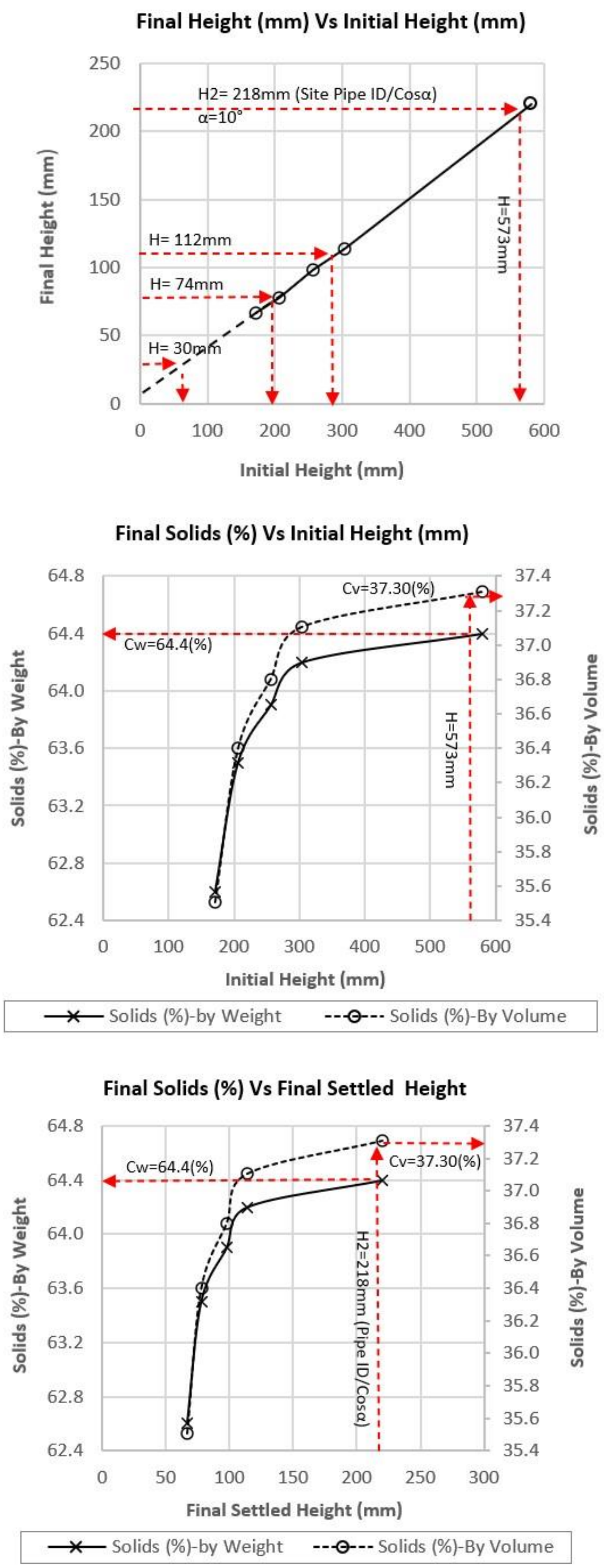

Figure 8 – Final settled bed depth and solids concentration estimated from the settling column tests

The recorded actual lengths of fully blocked pipes and the estimated maximum blockage length for different pipe diameters, slopes and lengths are summarised in Table 1.

As mentioned earlier and shown in the example profiles of Figure 4, not all of the inclination angles in the tested pipes resulted in all of the solid particles to flow to the lower end of the pipes. For inclination angles flatter than 30° (i.e. 10°, 15°, 20° and 25° slopes) a considerable amount of solids were settled along the pipe length forming a gentle bed profile toward the lower end (with an opening left on the top of the settled bed).

Table 1 – Recorded and estimated full-blockage pipe length for different pipes lengths, diameters and inclination angles

Pipe Diameter and Length	Full Blockage Length	Pipe Slope (Degree)						
		0°	5°	10°	15°	20°	25°	30°
ID=97mm L =1,000mm L/ID=10.3	Measured (mm)	0	0	40	90	130	180	260
	Estimated (mm)	0	0	377	377	377	376	375
	K	0	0	0.106	0.239	0.345	0.479	0.693
ID=97mm L =2000mm L/ID=20.6	Measured (mm)	0	0	77	210	290	420	530
	Estimated (mm)	0	0	755	755	755	753	751
	K	0	0	0.102	0.278	0.384	0.558	0.706
ID=64mm L= 1,000mm L/ID=15.6	Measured (mm)	0	0	42	90	150	220	270
	Estimated (mm)	0	0	387	387	387	385	385
	K	0	0	0.109	0.233	0.388	0.571	0.701
ID=25.4mm L=2,000mm L/ID=78.7	Measured (mm)	0	0	100	230	280	400	540
	Estimated (mm)	0	0	800	800	800	798	798
	K	0	0	0.125	0.288	0.350	0.501	0.677
Average "K" Value or Different Pipe Inclination Slopes		0.000	0.000	0.110	0.259	0.367	0.527	0.694

The K value which is defined as the ratio of the actual observed length of the fully blocked pipe to the estimated maximum length of the blocked pipe has been calculated from Equation (9) for each test and presented in Table 1.

$$K = \frac{L_{Blockage(Recorded)}}{L_{Blockage(Estimated)}} \tag{9}$$

From the average K values presented in Table 1 for each slope, it appears that the K value is a constant value for each slope independent of the pipe diameter and total length. Using the K factor, Equation (7) proposed for the estimation of full blockage pipe length can be adjusted to the following Equation (10):

$$L_{Blockage(Max)} = K \times \frac{C_{W(t1)} \times \rho_{m(t1)}}{C_{W(t2)} \times \rho_{m(t2)}} \times L_I \tag{10}$$

As the tested tailings slurry at 33% solids is below the segregation threshold limit (the segregation threshold for this slurry is 59% by weight) it is expected that the coarse and fine particles to segregate as they settle in the pipeline after a shutdown. To investigate this, samples were taken for PSD testing from the top and bottom of the fully blocked pipe section of the 97mm diameter pipe at 10°, 20° and 30° inclination slopes. A sample was also taken from the settled bed at the higher end of the pipe. The results of the PSD testing of the samples for different slopes are shown in Figure 9.

As seen in Figure 9, the samples taken from the bottom of the lower end of the fully blocked pipe sections are considerably coarser than the samples taken from the top of the pipe and the samples from the settled bed at the higher end of the inclined pipe, which confirms the occurrence of segregation of the material in the pipe as they have settled and formed the bed. It should be noted that the segregation of coarse and fine materials was also observed in the static settling column test starting at 33% solids (by weight).

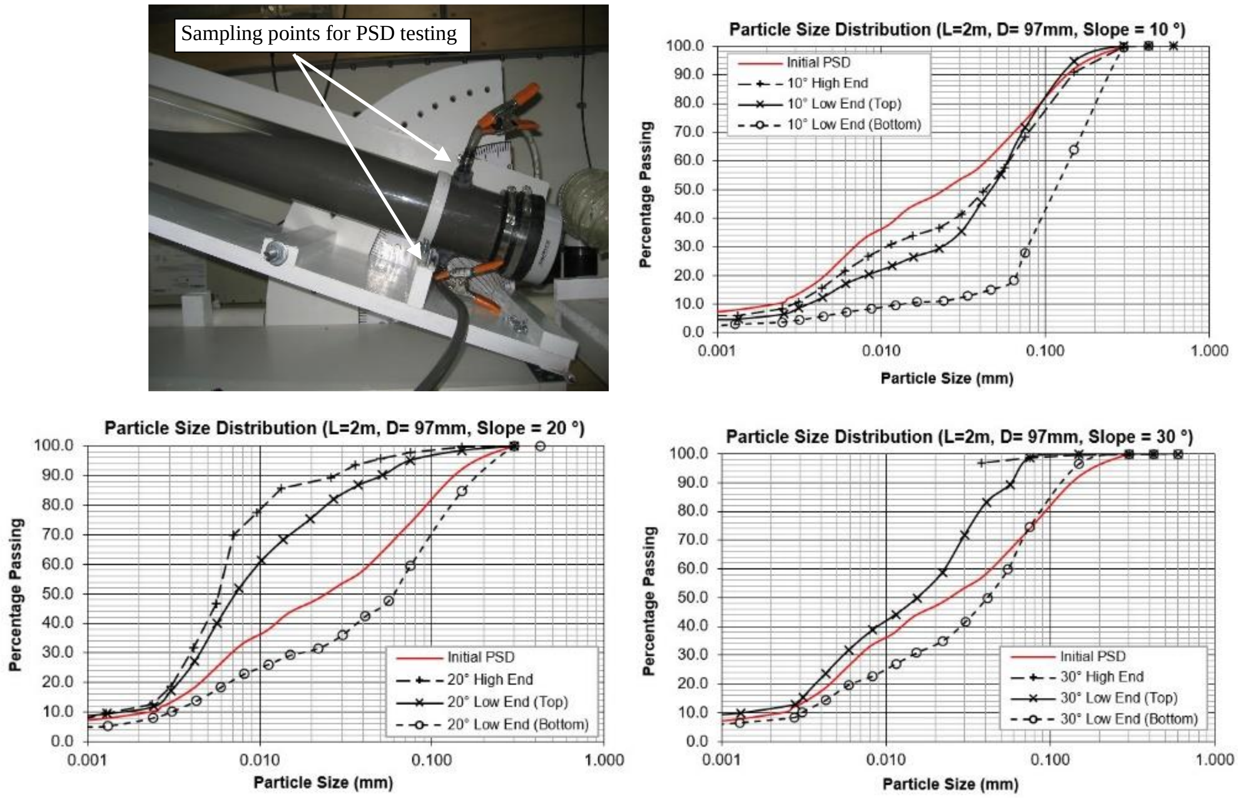

Figure 9 – PSD analysis for the samples taken from the 97mm diameter (2m long) pipe section with inclination slopes of 10°, 20° and 30°

4 PIPELINE RESTART PRESSURE TEST AND ANALYSIS

To evaluate the pressure required for re-establishment of the flow in a fully blocked section of the pipeline after a prolonged shutdown period (i.e. 24 hr), un-blockage and restart tests were performed in 97mm and 64mm diameter pipes using specifically designed and built testing rig.

As shown in Figure 10, the testing rig consists of 2m horizontal pipe sections with 1m extension pipe sections at either side of the horizontal sections. The 1m pipe pieces at the two sides of the horizontal section were assembled on adjustable slope frames to allow different inclination angle set-ups. This set-up was to simulate a slurry pipeline geometry and condition at the two sides of a river crossing bridge.

Pressure transducers connected to a data logger system were installed at the two ends of each pipe to record the pressure gradient in the system during the test. The required water flow and pressure to create the first opening in the slurry bed and re-suspend the particles were provided by a water pump equipped with a speed controller connected to a water tank. An in-line Coriolis mass flow and density meter connected to the datalogger system was used for recording the flow rate during the test.

The operating pipeline at the site had an internal diameter of 215mm and about 400m of the pipe length was at a maximum inclination angle of 10°. As demonstrated in Figure 8, the estimated maximum solids concentration that the slurry can reach in a fully-blocked section of the 215mm diameter pipeline at an inclination angle of 10° is 64.4% (by weight) which is equivalent to 37.3% (by volume).

The testing pipes were initially filled with slurry at a solids concentration of 64.4% (by weight). While the data logger was recording the pressure and flow rate from the instruments, the water pump was started at a very low speed, and then gradually the pump speed and hence pressure and flow were increased until the water flow was established in an opening formed at the top of the pipe and started to mobilise the solids particles.

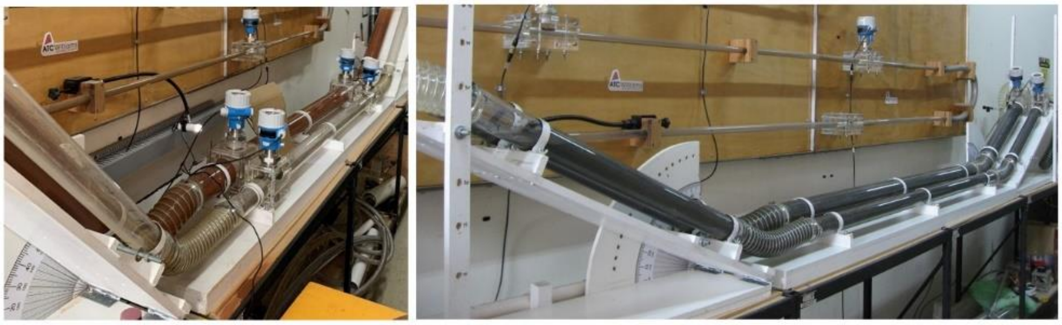

Figure 10 – Pipeline un-blockage and restart testing apparatus

Figures 11 and 12 present the recorded flow rate and pressure gradient during the un-blockage and restart test for the 97mm and 64mm diameter pipes respectively.

The comparison of the recorded flow rates in Figures 11 and 12 reveals that the un-blockage and the formation of the first opening in the slurry bed for the water flow in the two pipes have occurred at the same flow rate ((i.e. Q= 2400 l/hr) and after that point, the velocity of the water flow has been sufficient to re-suspended and remove the solids particles and enlarge the opening (i.e. pressure gradient has dropped).

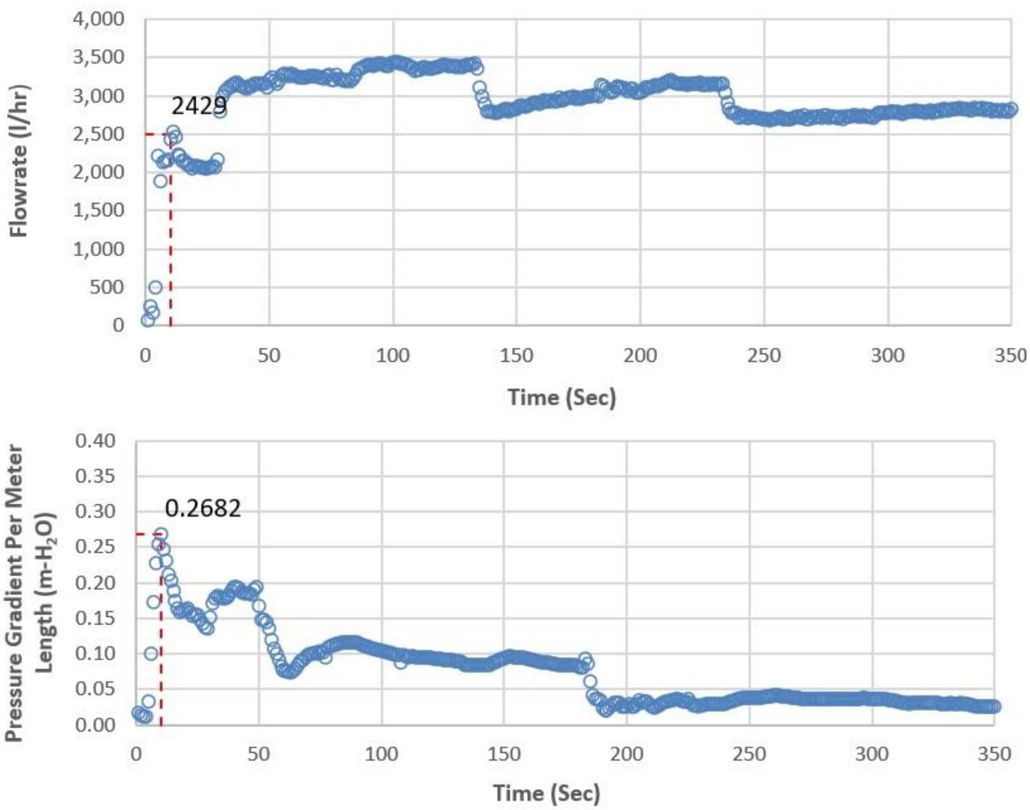

Figure 11 – Pressure and flowrate records during the un-blockage test with 97mm diameter pipe

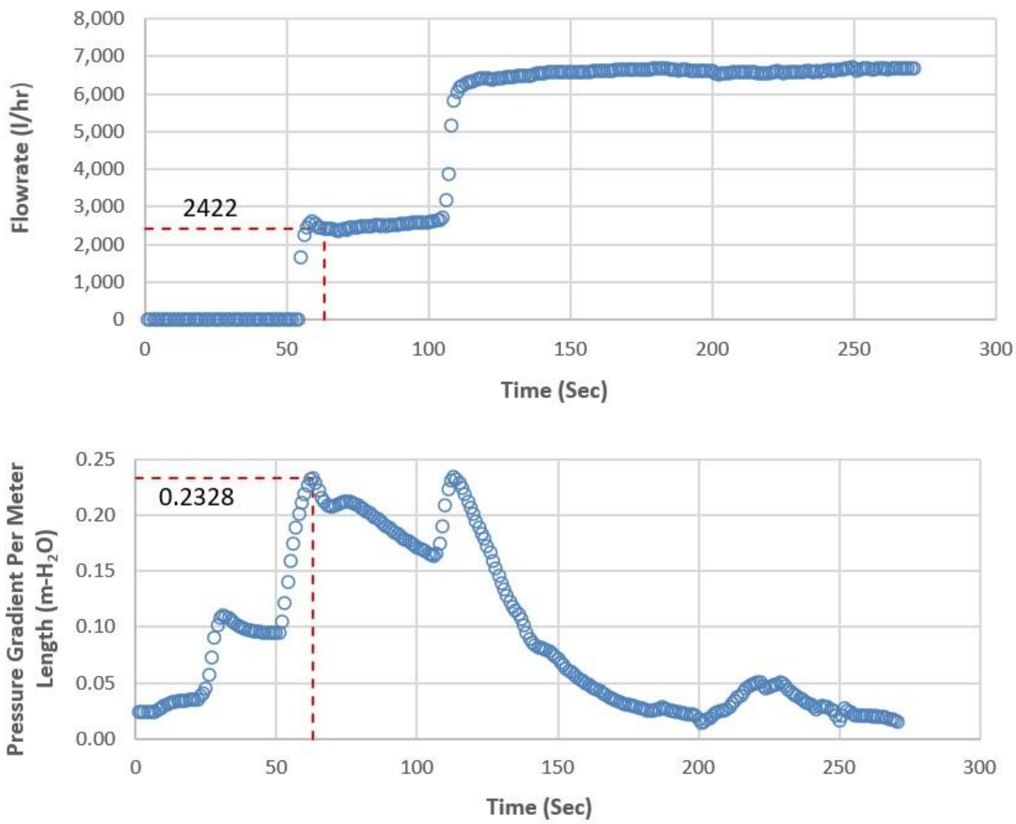

Figure 12 – Pressure and flowrate records during the un-blockage test with 64mm diameter pipe

One of the other important observations from the laboratory experiment is that the required pressure gradient to unblock the smaller pipe is lower than the pressure gradient required to create the first opening in the larger diameter pipe.

Assuming that the velocity required to re-suspend and remove the solids particles is the same for both pipe sizes and knowing that the recorded un-blockage flow rate was the same for the two pipes, it can be concluded that the cross-sectional area of the opening in the two pipes should be the same.

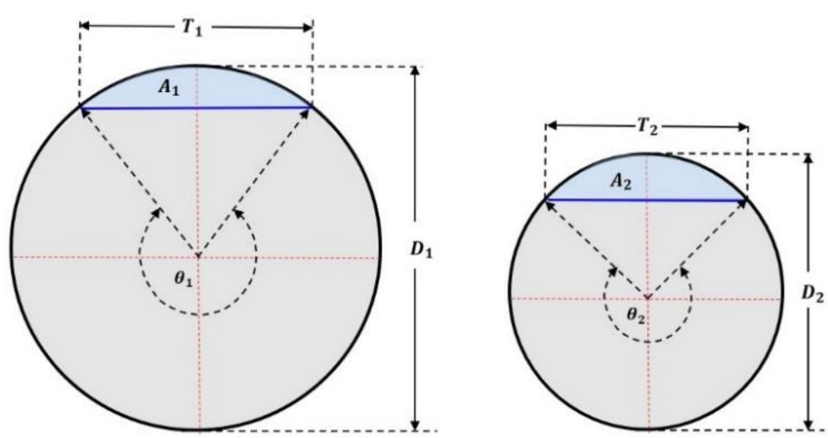

Figure 13 – First opening in the un-blockage test different size pipes

Considering the two different pipe sizes as shown in Figure 13, if we have the un-blockage pressure gradient and flow rate for one size pipe (diameter D_1) from the laboratory testing, then the following set of equations can be used to estimate the required pressure gradient for un-blocking of any other size pipe (diameter D_2).

The cross-sectional area (A) and other properties of the first opening at the top of the pipe for the passage of water flow can be estimated from equations (11) to (14) presented below:

$$A = \frac{1}{8}(\theta - \sin\theta)D^2 \tag{11}$$

$$T = D\sin\frac{\theta}{2} \tag{12}$$

$$W_P = D\left(\frac{\theta}{2} + \sin\frac{\theta}{2}\right) \tag{13}$$

$$D_h = \frac{4A}{W_P} = \frac{1}{2} \times \frac{(\theta - \sin\theta)}{(\frac{\theta}{2} + \sin\frac{\theta}{2})} \times D \tag{14}$$

The head loss in a pipeline with Length L can be estimated from the Darcy–Weisbach equation as below:

$$H_f = f \times \frac{L}{D_h} \times \frac{V^2}{2g} \tag{15}$$

Where f is the Darcy friction factor which can be estimated from the Colebrook formula:

$$\frac{1}{\sqrt{f}} = -2.0log\left(\frac{\varepsilon/D_h}{3.7} + \frac{2.51}{Re\sqrt{f}}\right) \tag{16}$$

The Reynolds Number Re in the Colebrook formula for water flow is estimated as:

$$Re = \frac{\rho V D_h}{\mu} \tag{17}$$

By substituting D_h form equation (14) and V from the continuity equation ($V = Q/A$) in equation (15), the following equation can be developed for the calculation of head loss in the water passage opening at the top of the pipe:

$$H_f = \frac{64\, fLQ^2}{gD^5} \times \frac{(\frac{\theta}{2} + \sin\frac{\theta}{2})}{(\theta - \sin\theta)^3} \tag{18}$$

If the flow rate Q_1 and head loss H_{f1} are recorded in the un-blockage test with pipe 1 (diameter D_1 and pipe length L_1), then equations (16), (17), (18) can be solved to find the pipe opening angle θ_1 and then θ_1 can be used in equation (11) to find the cross-sectional area of the first opening in pipe 1.

Now, if we consider pipe 2 (diameter D_2 and pipe length L_2), knowing that the flow rate required to create the first opening in the blocked pipe Q_2 is equal to the flow rate Q_1 recorded in the un-blocking test with pipe 1, also assuming the same velocity as pipe 1 will be needed to resuspend and remove the solids particles settled in any pipe size then it is concluded that:

$$V_1 = V_2 \rightarrow A_1 = A_2$$

From equation (14) the following equation (19) can be derived:

$$\left(\frac{D_1}{D_2}\right)^2 = \frac{(\theta_2 - \sin\theta_{2)}}{(\theta_1 - \sin\theta_1)} \tag{19}$$

The estimated θ_1 for pipe 1 and the known diameters of the two pipes (D_1 and D_2) can be used in equation (19) to obtain θ_2. Then the cross-sectional area A_2 and hydraulic diameter D_{h2} for the opening in pipe 2 can be estimated from equations (11) and (14) respectively.

Now, having D_{h2} and V_2 equations (15), (16), and (17) can be solved to obtain the required pressure gradient (head loss) in pipe 2.

The following equation (20) which is derived from equation (15) can be used as a check:

$$\frac{H_{f1}}{H_{f2}} = \frac{D_{h2}}{D_{h1}} \tag{20}$$

The above methodology can be applied to scale up or scale down the un-blockage pressure gradient from any size pipe to any size pipe.

To check the validity of the proposed method, the required pressure gradient for un-blockage of a fully blocked 64mm diameter pipe has been estimated from the data obtained from the testing with the 97mm diameter pipe. The estimated required pressure gradient for 64mm diameter pipe is 0.2229m (per m length of the fully blocked pipe) which compares very well with the recorded value of 0.2328m in the laboratory experience with the 64mm diameter pipe presented in Figure 12. The percentage of error is about 4.2%.

Table 2 summarises the results of applying the proposed analysis to the operating tailings pipeline at the site (ID= 215mm).

As presented in the table the estimated maximum pressure required to un-block the pipeline after 24hr shout-down is 77m (water head) and the available pumping pressure from the site pump station is 120m. Therefore, it is concluded that the un-blockage process on site (if needed) will be successful, and the pipeline can be recovered. It is worth mentioning here that the operating pipeline system at the site includes an automated flushing system that flushes the pipeline immediately after each shutdown.

Table 2 – Estimated pipeline blockage length and the required un-blockage pressure gradient for the site real size pipe

Description	Value	Unit
Operating pipeline slurry solids concentration (by weight)	33	%
Internal diameter of the pipeline	215	mm
Total pipeline length	1300	m
Total length of the pipe on 10° slope or steeper slope	400	m
Estimated solids concentration in the pipeline 24hr after shutdown (by weight)	64.4	%
Assumed (K) factor for 10° and steeper inclination angle (1)	1	
Estimated maximum total length of the fully blocked pipe	205.0	m
Recorded pressure gradient for un-blockage for 97mm pipe at the lab	0.2682	m/m
Estimated pressure gradient for un-blockage for 215mm pipe on site	0.3755	m/m
Estimated total pumping pressure required for un-blockage	77.0	m
Available pumping pressure	120	m

Note 1: Based on the data presented in Table 1, the estimated "K" value for 10° inclination angle is 0.11 which if applied, then the total length of the fully blocked pipe is reduced to 22m.

5 STEP-BY-STEP PROCEDURE FOR PIPELINE RESTART ASSESSMENT

The laboratory experiments, discussion, and analysis presented in the previous sections of this paper are summarised below in the form of a step-by-step procedure that can be applied as a design tool for checking a slurry pipeline system capacity for un-blockage after a shutdown:

Step 1: Conduct a series of pipe inclination angle tests with the slurry sample from the site (the same solids concentration as the operating pipeline) to define the critical angle (α) that can potentially cause a full blockage at the low points of the pipeline profile (Figures 2, 3, and 4). The "K" value for the tested slurry can also be estimated from these tests (conservatively a K = 1 can be adopted for the analysis);

Step 2: Conduct a series of settling column (Figure 6) tests with starting solids concentration the same as the site operating pipeline and different starting column heights and generate graphs similar to Figures 7 and 8.

Step 3: Evaluate the designed (or existing) pipeline profile and estimate the total length of the pipeline that is installed at an angle steeper than the critical angle estimated in Step 1.

Step 4: From the setting curves developed in Step 2 and knowing the site Pipe diameter D_2 and $D_2/\cos\alpha$ from the pipeline profile assessment in Step 3, estimate the maximum solids concentration that the slurry can reach in the pipeline after shutdown ($C_{W(t2)}$).

Step 5: Use equation (10) to estimate the maximum expected length of the pipeline that can potentially become fully blocked after a shutdown ($L_{Blockage(Max)}$).

Step 6: Perform an un-blockage and re-start test in the laboratory with a known size pipe (diameter D_1) filled initially with slurry at solids concentration $C_{W(t2)}$ and record the re-start flowrate ($Q_{1)}$, the required un-blockage pressure gradient H_{f1}.

Step 7: Solving equations (16), (17), and (18) obtain the initial opening angle θ_1 for the tested pipe.

Step 8: Using Equation (19) estimate the initial opening angle for the site pipe θ_2.

Step 9: Solve equations (16), (17), and (18) to obtain the required pressure gradient H_{f2} and total pressure at the site for un-blockage of the maximum length of the pipeline that can potentially be blocked at a shutdown ($L_{Blockage(Max)}$).

Step 10: Compare the available pressure gradient from the site pumping system to the estimated required un-blockage pressure gradient H_{f2}.

6 CONCLUSIONS AND REMARKS

The observations and collected data from the experimental tests were analysed and used to develop a step-by-step procedure for prediction of the length of pipeline that can potentially be blocked at shutdowns of a real size slurry pipeline with known profile and geometry. The proposed methodology can be used as a design validation tool for checking the required pressure gradient to flush and restart the pipeline after a shutdown. Some of the findings from the current study can be summarised as below:

- The observations show that the dominant mechanism that causes the full blockage of sections of the slurry pipeline after a shutdown, is the migration of solid particles from higher points of the pipeline toward the lower points in the form of a "density current". This mechanism starts almost immediately after the shutdown as the solids and liquid separation process starts in the pipeline.

- Provided that the shutdown time is long enough and the length of the inclined section of the pipeline is sufficient, a full pipe blockage at the lower point of the pipeline can form even for an inclination angle as gentle as 10°.

- The length of the pipeline that can potentially be fully blocked during a prolonged shutdown period, depends on the slurry initial solids concentration, the inclination angle, and the settling behaviour of the slurry solids particle. This length can be estimated with reasonable accuracy from basic laboratory settlings tests and the geometry of the pipeline.

- A "K" factor has been defined in the current study as the ratio of the recorded actual blocked length of the pipe to the theoretically estimated blockage length for different pipeline inclination angles. Further testing and research are recommended to obtain a better understanding of the effect of slurry properties and pipe inclination angle on the "K" factor.

- The ultimate solids concentration that the slurry at the low points of an inclined pipeline can reach following a shutdown, is not influenced by the length of the inclined section of the pipe. It is rather governed by the diameter of the pipe, the angle of inclination, and the settling characteristics of the slurry.

- When re-starting a fully blocked pipe with water, the first opening in the mass of thickened slurry in the pipeline always appears as a small passage that forms at the top of the pipeline where the settled particles are looser. After the initial opening is formed in the pipe and the water flow is established the pressure in the pipeline suddenly drops.

- If the water pressure is kept behind the blocked section of the pipeline, this initial small opening on the top of the pipe will enlarge gradually and the water flow washes more solids particles out of the blocked pipe until a point that the entire deposited solids bed is resuspended and flushed out of the system.

- The time that takes for the first opening to form in a fully blocked pipe depends on the density of the thickened slurry in the pipeline, the length of the fully blocked pipe section, water pressure that the pumping (or gravity flushing system) can apply to the upstream end of the blocked pipe section and also the re-suspendability behaviour of the solids particles.

- The observations from the current study show that the first opening in the pipeline happens at the same flow rate for pipes of different sizes. This is believed to be due to the fact that a certain velocity is required to remobilise the solids particles to create the first opening.

- Further research and laboratory experiments with different slurries are recommended to validate the findings from the current study.

7 REFERENCES

1) Wilson, K.C., Addie, G.R., Sellgren, A. and Clift, R. (2010), Slurry transport using centrifugal pumps, 3rd Edition, Springer. Chapter 8. Vertical and Inclined Slurry Flow, pp 172-189.

2) Shook, C.A., Rollins, J., and Vassie, G.S.V. (1974) Sliding in Inclined Slurry Pipelines at Shutdown. Canadian Journal of Chemical Engineering, Vol 52, June, pp 300-305.

3) Shook, C.A. and McLeod, D.J. (1975). The effect of Line Length for Inclined Slurry Pipelines at Shutdown. Canadian Journal of Chemical Engineering, Vol. 53, December, pp 594-598.

4) Aude, T.C., and Gandhi, R.L. (1977), Research and Development for Slurry Pipeline System design. United States: p.56, 2nd Int. Slurry Transportation. Assoc. Tech. Conf. Proc.; (United States).

5) Gandhi, R.L. and Aude, T.C. (1978), Slurry Pipeline Design-Special Considerations. Hydrotransport 5, BHR Group, Federal Republic of Germany. p J1-1.

6) Shou, G., (2004), Slurry Pipeline Blockage, Theory and Practice. Hydrotransport16 BHR Group, pp 623-629.

7) Thomas, A.D., Gaultier, P. and Hoskins, M. (2002) Two 300 km Concentrate Pipelines Compared. Century Zinc/Lead Concentrate Pipeline, Australia and Antamina Copper/Zinc Concentrate Pipeline, Peru, Hydrotransport 15 Conference, BHR Group, Banff, Canada. pp 623-629.

8) Wilson, K.C. and Tse, K.P. (1984) Deposition Limit for Coarse-Particle in Inclined Pipes., 9th International Conference on Hydraulic Transportation of Solids In Pipes, Rome, Italy. Pp 149-161.

9) Spelay, R.B., Gillies, R.G., Hashemi, S.A., Sanders, R.S. (2014) Effect of Pipe Inclination on the Deposition Velocity of Settling Slurries, Hydrotransport19, BHR Group, Golden, Colorado, USA, pp 147-16.