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ANALYSIS OF FRICTION PRESSURE GRADIENTS DURING SLURRY PIPELINE RESTART

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Abstract: This paper presents an analysis of the variation in pipeline friction pressure gradient as a slurry pipeline is restarted from a shut-down condition with a settled bed. A resuspension mechanism is described whereby flow initially occurs only in the free area above the settled bed, and then, as the flowrate is increased, a threshold velocity is reached at which solids begin to be eroded from the surface of the settled bed. It is proposed that as the flowrate increases, an equilibrium condition is maintained between the flow area above the eroding settled bed and the flowrate, such that the velocity above the bed equals the resuspension velocity. Friction pressure gradient and slurry flowrate data together with visual observations have been collected from a restart test in a recirculating pipe loop. The data shows an increasing pressure gradient with increasing flowrate as the settled bed is eroded and re-suspended. The pressure gradient reaches a maximum at a point shortly before the bed is fully re-suspended. The relationship between friction pressure gradient and flow rate is modelled based on the assumption that the flow velocity above the bed remains at the resuspension velocity until the bed is fully eroded. Although a number of opportunities to improve the analysis have been identified, encouraging agreement between experimentally measured data and the calculation is achieved. It is suggested that this analysis could be incorporated in the design process of slurry pipeline systems in order to assess the pump requirements for pipeline restart form a shut-down with settled bed condition.

KEY WORDS: Slurry pipeline restart, resuspension, settled bed

NOTATION

A_1	cross-sectional area of the flow area above settled bed
A_2	cross-sectional area of the settled bed
C_{bed}	solids packing concentration in settled bed
D	pipe internal diameter
D_{hyd}	hydraulic diameter of non-circular flow area
k_{bed}	hydraulic roughness of settled bed surface
k_{pipe}	hydraulic roughness of pipe surface
k_{hyd}	effective hydraulic roughness for the flow area above the settled bed
Q_m	mixture (slurry) flow rate
V_1	flow velocity in the flow area above the settled bed
V_{resusp}	re-suspension velocity
∇_s	volume of solids
∇_w	volume of liquid

1. INTRODUCTION

Usual and recommended operating practice for most slurry pipeline systems is for the pipeline to be flushed (slurry displaced with water) before the pipeline system is shut down. This is done primarily to avoid pipeline blockage and inability to restart the pipeline. Blockage would typically be due to the formation of plugs of solids in the pipeline and / or not being able re-suspend the solids which have settled as a bed on the pipe invert.

If the pipeline is shut down without flushing (intentionally or unintentionally, due to a power failure, for example) the solids and water in the slurry will segregate and the solids will form a settled bed on the pipe invert. This segregation can occur in a matter of seconds (for a coarse, fast settling slurry) or over a number of hours (for a very fine, or stable slurry). Considering purely horizontal piping, the fraction of the pipe cross-sectional area occupied by the settled bed will depend on the in-situ slurry concentration at shut-down and the natural packing concentration of the solids. This then dictates the free flow area above the settled bed (occupied by water).

Assuming that the pipeline restart is achieved by steadily ramping up the flowrate, it is expected that flow will initially occur only in the free flow area above the bed, and will progressively erode the bed until all solids are re-suspended and full slurry flow is established. A good description of the pipeline restart process for long-distance slurry pipelines is given by Thomas et al (2002).

Restart of a slurry pipeline with a settled bed is a situation that is considered likely to occur for almost every slurry pipeline system at one time or another. It is thus surprising to the author that a literature search has not been able to identify any literature dealing specifically with determining the pipeline friction pressure gradient during the restart process. The motivation for this work was thus to investigate the friction pressure gradient during restart, with the objective of being able to make an estimation of the variation of friction pressure gradient during a pipeline restart, and in particular the peak driving pressure required during restart.

2. PROPOSED RESTART AND RESUSPENSION MECHANISM

This analysis of pipeline restart considers a horizontal pipeline with the slurry solids all contained in a settled bed on the bottom of the pipe. Specifically this analysis considers a non-cohesive, settling slurry. The geometry considered is shown in Figure 1, with the settled bed and the free area above the bed defined in terms of the half-angle beta. This settled bed and free flow area geometry is as defined by Wilson et al (1972) in assessment of the slip point of a settled bed, and in many developments on this concept, including modelling of settling slurry flow considering a contact load (stationary or sliding bed) and layer of fluid and suspended solids flowing above (Wilson, 1976).

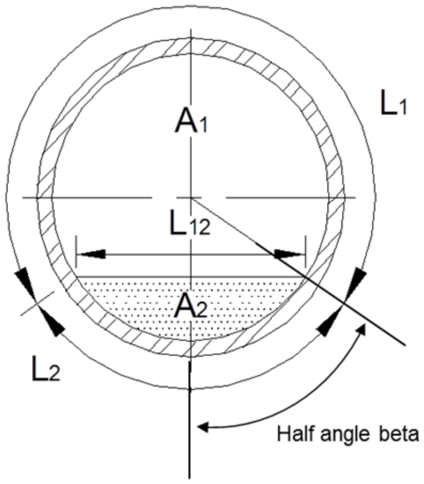

Fig.1 Definition of the Geometry of the Settled Bed and Free Area Above

The slurry pipeline restart and resuspension process in an industrial slurry pipeline system is assumed to be as follows:

1) Restart is initiated with the pump/s in the system started and slowly ramped up to steadily increase the pressure driving the flow.
2) A unit length of the pipeline at a distance away from the pumps or other disturbance is considered.
3) Flow is initiated in the free area above the bed only. The fluid occupying this area initially flows with no solids in suspension and no solids transport.
4) As the flow rate is increased, the flow velocity in the area above the bed reaches the threshold necessary to start suspending solids from the surface of the bed.
5) Now, as the flow rate continues to increase:
   i. The surface of the bed is eroded and suspended, such that the flow area enlarges for the velocity in the flow area to remain at the threshold suspension velocity (a changing "equilibrium" condition).
   ii. In this process it is expected that the value of the threshold suspension velocity changes with the increasing flow area and the increasing solids concentration in the mixture flowing over the bed.
6) Once the bed has been entirely eroded and all solids are in suspension, the composition of the slurry will match that when the pipeline was shut down.

The focus of this paper is on calculating the variation of the pipeline friction pressure gradient during this restart process.

Restart test data has been collected (described below) and then a calculated pressure gradient versus flow rate trend (based on the restart mechanism just described) is compared to the data in Section 4 "Modelling Pipeline Restart".

3. RESTART TESTS AND MEASURED DATA

3.1 RECIRCULATING SLURRY PIPE LOOP

Slurry pipeline restart tests have been performed in a recirculating slurry pipe loop in the Paterson & Cooke Slurry Test Facility in Cape Town, South Africa. The test facility incorporates pipe loops of nominally 100 mm, 150 mm, 200 mm and 250 mm diameter pipe (see Figure 2). The slurry flow is driven by a centrifugal slurry pump with variable speed electric drive. During a test, the flow is directed through one pipe loop only (the others are closed off by means of isolation valves).

Each pipe loop incorporates a clear PVC observation pipe section, where visual observations of the slurry flow are made. The slurry flow rate in the pipe loop is recorded by means of a magnetic flow meter. The slurry density is determined from a combination of measured flow rate (magnetic flow meter) and measurement of pressure drop across a venturi installed in a vertical pipe section. The pipeline friction pressure gradient is measured in appropriate straight pipe lengths fitted with static pressure tapings and differential pressure transducers.

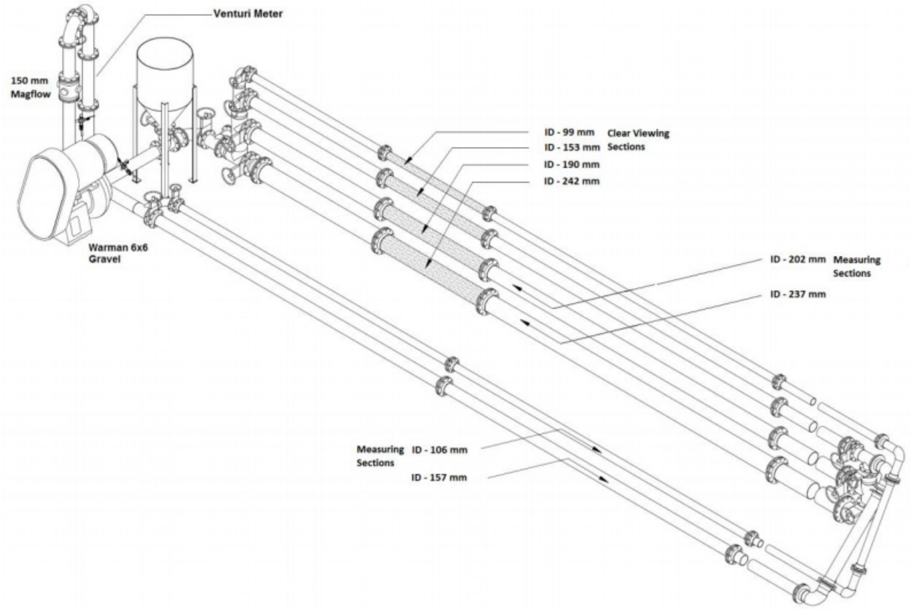

Fig.2 Recirculating Pipe Loop Facility

3.2 RESTART TESTS

Pipe loop pressure gradient tests (measuring friction pressure gradient as a function of pipeline velocity) and restart tests were performed with a slurry of coarse salt (NaCl, solids density 2125 kg/m^3) in a saturated salt solution (saturated solution density 1200 kg/m^3 and viscosity 0.0023 Pa.s). The particle top size was 2 mm, median grain size 600 microns and approximately 5% sub 100 microns. This slurry was used only because it was available in the pipe loop from a commercial test programme. The restart test was done in the 150 mm NB pipe loop (157 mm diameter pressure gradient measurement pipe section and 153 mm diameter clear observation pipe section).

The restart test procedure was as follows:

1) After a period of circulating the slurry in the pipe loop (typically after a conventional pressure gradient test), the pipe loop was shut-down. This was done by progressively reducing the flow rate from a condition where the slurry was fully suspended, to zero flow, over a period of typically 30 seconds. This left the solids approximately uniformly distributed as a settled bed throughout the horizontal piping in the pipe loop.
2) The pipe loop was left undisturbed for a selected shutdown duration (shutdown periods of 15 minutes, 2 hours, 16 hours were applied).
3) For the pipe loop restart, the slurry pump was started and run at minimum speed, then ramped up at a controlled rate. During the restart the pipeline friction pressure gradient and slurry flow rate were logged. The flow rate ramp-up from zero to the point at which the settled bed was fully re-suspended occurred over a period of approximately two minutes.
4) Observations were made of the slurry flow conditions in the clear viewing pipe section. For this slurry it was observed that with increasing flow rate, the stationary bed was progressively eroded from the top down (as opposed to the bed sliding or being fluidized en masse which are other restart modes which may be seen for other slurries). In particular, the flow rate at which the last of the settled bed was eroded and re-suspended was recorded as the "resuspension velocity" in the 153 mm diameter viewing pipe.

The emphasis in these tests was on recording the trend in pipeline pressure gradient as the flow rate was steadily progressed from zero to beyond the point where the bed was fully re-suspended.

3.3 RESTART TEST RESULTS

3.3.1 Deposition Velocity and Resuspension Velocity

The stationary deposition velocity is the pipe flow velocity at which stationary particles are first observed on the pipe invert as the flow rate in the pipe loop is steadily reduced from the test maximum to the test minimum. The stationary deposition velocity in the 153 mm bore viewing pipe had been recorded during previous tests over a slurry concentration range of 7% to 32% by volume. This stationary deposition velocity data with 2^{nd} order polynomial trend line is shown in Figure 3. Also shown are the resuspension velocity measurements from three shut-down tests (shut-down durations of 15 minutes, 2 hours and 16 hours), all at slurry concentration 19%v. There is a significant difference between the stationary deposition velocity and the resuspension velocity (+0.46 m/s to +0.78 m/s, increasing with increasing shut-down time).

To facilitate the modeling of the pipeline restart and settled bed resuspension (described in Section 4) a mathematical relationship between resuspension velocity and slurry concentration is required. In the absence of any other data, an assumption has been made that this offset is constant for the full concentration range from zero to 32%v. This is indicated in Figure 3 by the off-set polynomial trend lines. Certainly refinement of the resuspension velocity trend with concentration needs to be investigated in future work.

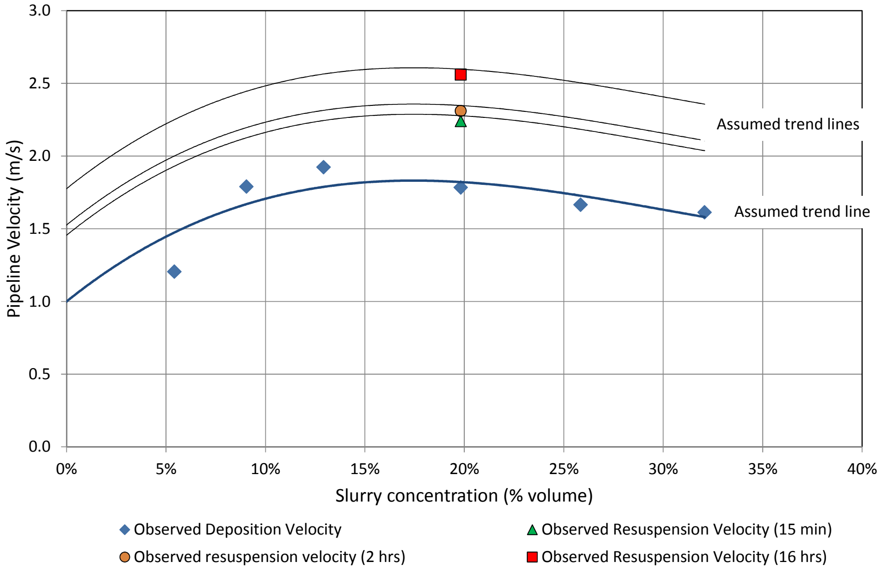

Fig.3 Deposition Velocity and Resuspension Velocity Data and Trend Lines

3.3.2 Pressure Gradient and Flow Rate Data

The restart test results for the three restart tests corresponding to shut-down durations 15 minutes, 2 hours and 16 hours are presented in Figure 4 in the form of a plot of pipeline friction pressure gradient versus slurry flow rate. Also shown for comparison is the pressure gradient versus flow rate data from the pipe loop pressure gradient test (recorded in the flow rate range 75 to 35 ℓ/s which is all above the stationary deposition velocity). The test results show the following:

1) With increasing flow rate from the zero flow shutdown condition to approximately 20 ℓ/s, the friction pressure gradient trends for the three tests are coincident. This region corresponds to liquid only flow above the settled bed, without any resuspension of solids.
2) At approximately 20 ℓ/s flow rate, solids begin to be eroded from the settled bed and suspended in the flow above the bed. This point corresponds to the resuspension velocity being reached for the flowing mixture (being liquid only at this point) in the flow area above the bed.
3) Further increase in flow rate results in further erosion of the bed, increasing the flow area. If the rate of increase in flow is not too fast, it is considered reasonable to assume that the relationship between flow rate and flow area above the bed is such that the velocity in the flow area will be equal to the

resuspension velocity (noting that the magnitude of the resuspension velocity will vary with flow area and flowing slurry concentration).

4) The approximately linear increase in pressure gradient in the flow rate range 20 to 35 ℓ/s is assumed to be related to the approximately linear increase in slurry concentration and density with increasing flow rate in this region.
5) The leveling-off (even reduction) of pressure gradient with increasing flow rate in the rate range 35 to 35 ℓ/s is attributed to reducing contribution of the settled bed hydraulic roughness (which is significantly higher than the pipe hydraulic roughness) with reducing settled bed surface area (L_{12} in Figure 1).
6) Once the settled bed has been entirely eroded and re-suspended (occurring at different flow rates as indicated for each of the three tests) the pressure gradient data follows the expected trend for fully suspended flow. The reason for the spread in the pressure gradient measured in this region for the four data sets is not clear.

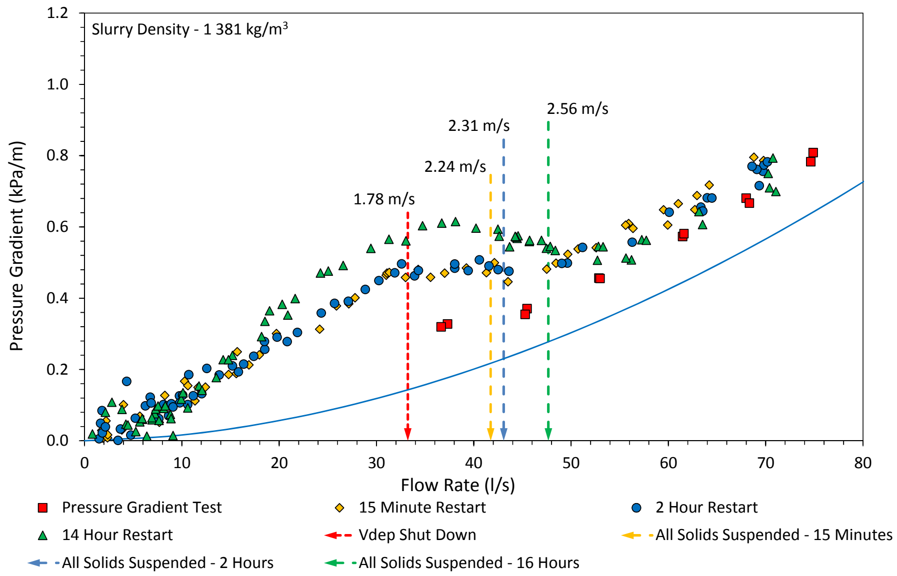

Fig.4 Pressure Gradient Data from Conventional Pressure Gradient Test (Red Squares) and from the three Restart Tests. Deposition Velocity and Resuspension Velocity Values Indicated

Other (general) observations are as follows:

1) Velocities significantly higher than the stationary deposition velocity are required to re-suspend the solids.
2) The velocity required to achieve full resuspension increases with increasing shutdown time.
3) The peak pressure gradient during restart increases with increasing shut-down time.

4. MODELLING PIPELINE RESTART

Following the restart mechanism already described, the friction pressure gradient is calculated by considering the flow rate and mixture composition in the flow area above the settled bed. It is assumed that the bed remains stationary (does not begin to slide) during the restart, and flow through the interstices in the settled bed is ignored.

4.1 KEY PARAMETERS RELATING TO THE FLOW AREA

With reference to the pipe cross-sectional geometry as defined in Figure 1, the flow velocity in area A1 is given by:

$$V_1 = \frac{Q_m}{A_1} \tag{1}$$

The hydraulic diameter for the flow area A_1 is given by:

$$D_{hyd} = \frac{4 \times Flow\ Area}{Flow\ Area\ Perimeter} = \frac{4 \times A_1}{L_1 + L_{12}} \tag{2}$$

The hydraulic roughness of the flow area is averaged from pipe surface roughness and the settled bed surface roughness, considering the contribution of each to the flow area perimeter:

$$k_{hyd} = \frac{k_{pipe} \times L_1 + k_{bed} \times L_{12}}{L_1 + L_{12}} \tag{3}$$

The settled bed surface roughness is taken to be equal to the P90 particle size. There is clearly scope for refining this value. For example, Wilson (1976) suggests that the friction factor at the "mobile" bed surface could be twice that given by the Nikuradse formula for fixed grain roughness. What "grain roughness" size is appropriate for a slurry with relatively wide particle size distribution is however not clear. Krupička & Matoušek (2010) and Miedema & Matoušek (2014) present a number of methods for estimating the hydraulic roughness of the settled bed surface, typically incorporating the Shields number.

4.2 RESUSPENSION VELOCITY

Key to the analysis is determining the resuspension velocity as it varies with slurry concentration and flow area hydraulic diameter, D_{hyd}. For this analysis, the variation of resuspension velocity with slurry concentration as shown in Figure 3 is applied. The effect of flow area is accounted for by assuming a square root relationship with flow area hydraulic diameter, as when applying Froude number scaling in deposition velocity scaling:

$$V_{Resusp}\ in\ D_{hyd} = V_{Resusp}\ in\ D \times \left(\frac{D_{hyd}}{D}\right)^{0.5} \tag{4}$$

4.3 TRACKING MIXTURE COMPOSITION IN THE FLOW AREA

4.3.1 Initial Conditions

The settled bed cross-sectional area A_2 before restart is estimated from the in-situ slurry concentration at shut-down and the bed packing concentration, C_{bed}. The bed packing concentration will need to be measured for the slurry in a bench-top settling test. The modeling of the pipeline restart is based on tracking the variation of flow area A_1, velocity in the flow area, V_1 and slurry concentration in this area, C_1 as the flow rate is ramped up. The analysis can be done by means of a step-wise calculation in a spreadsheet, with flow rate increased incrementally.

When flow is first initiated at restart, the velocity of the fluid occupying area A_1 steadily increases from zero. Only once the flow velocity V_1 reached the resuspension threshold will solids begin to be eroded from the top of the settled bed and conveyed in the fluid flow. The composition of the flow above the bed is tracked by considering the initial fluid volume per unit length for area A_1, and the volume of fluid and solids added to this volume as the bed is progressively eroded. This calculation is detailed below, considering the two phases in the restart process.

4.3.2 Case: Flow Velocity < Resuspension Threshold Velocity

While the flow velocity in flow area A_1 is less than the threshold of resuspension, no solids are re-suspended and the solids concentration in the flow is zero. The flow area remains unchanged with increasing flow rate until the resuspension threshold velocity is reached.

4.3.3 Case: Flow Velocity = Resuspension Threshold Velocity

Once the resuspension threshold velocity is reached, each increment in flow rate results in additional resuspension of solids from the bed, reducing the bed area A_2 and increasing the flow area A_1 by increment delta A (ΔA). The incremental volume of solids and incremental volume of liquid per unit length of pipeline transferred from the settled bed (A_2) to the flow area (A_1) is given by:

$$\Delta\nabla_s = \Delta A \times C_{bed} \,, \tag{5}$$

and:

$$\Delta\nabla_w = \Delta A \times (1 - C_{bed}). \tag{6}$$

The concentration of the slurry flowing above the bed is calculated for each flow rate increment by tracking the volume (or mass) of solids and liquid moving from the settled bed to the flow area as the bed is progressively eroded with increasing flow rate.

4.4 RESTART PRESSURE GRADIENT CALCULATION

The relationship between pressure gradient and flowrate during the restart process is determined by considering the flow velocity V_1 in flow area A_1 (with hydraulic diameter D_{hyd} as defined in Equation 4). The composition of the slurry occupying area A_1 is determined as described above. Calculation of the friction pressure gradient can be done by applying a suitable slurry friction pressure gradient prediction model, with inputs velocity V_1, diameter D_{hyd} and slurry concentration C_1. In the analysis presented here, the "equivalent-fluid" approximation is used (treating the head-loss gradient for slurry flow as equal to the head-loss gradient for an equivalent flow of liquid only). The very convenient pseudo-fluid approach is used for convenience here, but is expected to provide a reasonable approximation for this slurry for velocities ≥ the resuspension velocity. It is to be expected that the pressure gradient prediction would be improved by adopting an analysis specifically applicable to slurry flow over a stationary bed such as has been developed by Matoušek (2007).

Figure 5 presents the data from the three restart tests (15 minute, 2 hour and 16 hour shut-down) in the form of a plot of measured pipeline pressure gradient versus flow rate. Also shown are calculated pressure gradient versus flowrate trends for the 15 minute shut-down and the 16 hour shut-down. Two key observations are made regarding these results, as discussed under separate headings below.

4.4.1 Effect of Shut-Down Time

The calculation predicts the observed increase in restart peak pressure gradient with increasing shut-down time. This is achieved by incorporating in the calculation the observed increase in resuspension velocity with increasing shut-down time.

This analysis made use of measured values of the resuspension velocity in order to perform the calculation. It is clear that this requires access to a facility to make these measurements. It is expected that further investigation of the resuspension velocity may allow for development of correlations for predicting resuspension velocities, in much the same way as has been done for the stationary deposition velocity.

4.4.2 Restart Pressure Peak

The calculation over-predicts the magnitude of the restart peak pressure gradient by approximately 20%. In the case of this data and analysis, the over-prediction begins at the point where approximately half of the settled bed has been re-suspended. The author believes that this may be associated with the way that the hydraulic roughness of the settled bed is incorporated in the slurry friction pressure gradient calculation: The weighted average hydraulic roughness (as defined in Equation (3)) is applied in the friction pressure gradient calculation. This appears to be appropriate for the fluid-only flow (velocities < the resuspension velocity), where the velocity distribution in the flow area is approximately symmetrical around the centroid. However, once sufficient of the bed has been re-suspended, the solids concentration in the flow area is increased to the point that the velocity and distribution is significantly asymmetrical, with velocities lower than the mean at the interface with the hydraulically rough bed, and velocities higher than the mean at the interface with the hydraulically smooth pipe. In this scenario the roughness of the bed should have a much reduced effect, rather than the equal weighting that it is given in this analysis. This could be the subject of a separate investigation.

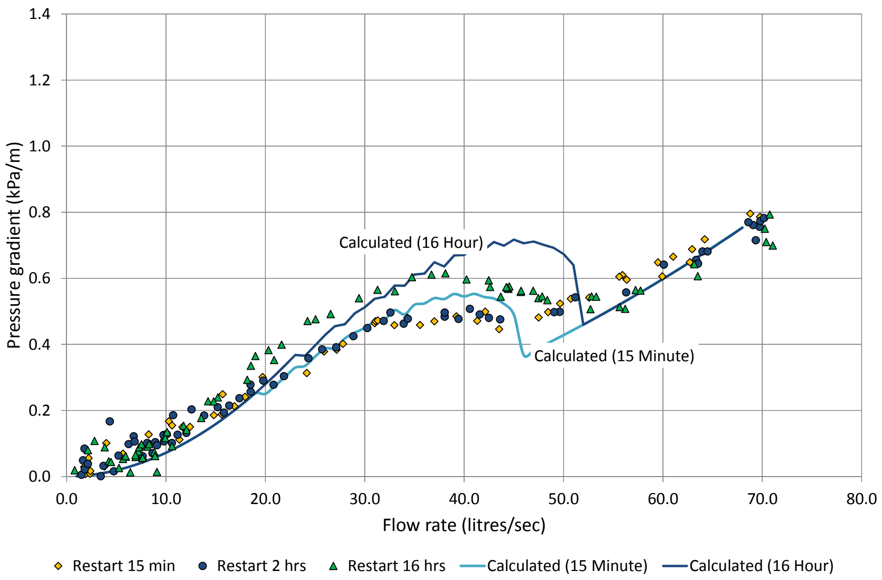

Fig.5 Restart Test Data and Calculation Predictions: 15 Minute Shut-Down and 16 Hour Shut-Down

5. OPPORTUNITIES FOR REFINING THE ANALYSIS

The analysis as presented here incorporates a number of assumptions and simplifications which could be investigated for opportunities to improve accuracy. Aspects of the analysis which could be refined include:

1) Consideration of layering of the settled bed: It is expected that, particularly in the case of slurries with a wide particle size distribution, the settled bed will not be homogeneous but will layered in terms of particle size and packing concentration. This could be incorporated in the analysis by relating these parameters to bed depth.
2) Consideration of vehicle density and viscous properties: In line with layering of the settled bed as described above, the finest (slowest settling) particles in the slurry will occupy the top layers of the settled bed. By considering these fine-particles layers being re-suspended first, the effect of these fines on the fluid properties (density and viscous properties) is expected to modify the resuspension velocity.
3) Time dependence of the settled bed properties: The results of the restart tests after varying shutdown periods has indicated that there is a clear time dependence of the restart. This is assumed to be related to progressive settlement of the bed which could be investigated further.

6. CONCLUSIONS

This paper has presented a proposed analysis methodology for estimating slurry pipeline friction pressure gradient variation with flowrate as the pipeline is restarted from a shutdown condition with a settled bed. Although a number of opportunities to improve the analysis have been identified, encouraging agreement between experimentally measured data and the calculation output is achieved.

It is suggested that this analysis should be incorporated into the design process of slurry pipeline systems where appropriate in order to assess the pump requirements for pipeline restart from a shut-down with settled bed condition.

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