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Pressure instrument slack flow detection – three methods to determine flow status of a paste reticulation system

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Abstract

One of the most significant operational problems that paste backfill systems face is detection and mitigation against slack flow. Slack flow occurs when there is an excess of gravity head energy within the reticulation system, resulting in high-velocity conditions that increase wear. It is a primary cause of borehole failure. Hydraulic modelling can predict where slack flow might occur and is a principal component in designing a reticulation system to mitigate against slack flow. However, hydraulic modelling relies on accurate rheological measurements to estimate friction losses and requires a distinct predetermined pipeline route. Both these factors become increasingly hard to evaluate during operation; variation in tailings mineralogy or PSD can cause significant shifts in the rheological characteristics of the paste, and as-built reticulation networks frequently differ from the designed routing and/or pipe class. Furthermore, providing real-time feedback to plant operators via hydraulic grade lines is difficult.

In a study conducted by Paterson & Cooke for Boliden's Garpenberg mine located in central Sweden operating a paste backfill system, three distinct methods were developed to detect slack flow in real-time from underground Pressure Instruments (PI). These methods provided immediate feedback to plant operators on whether the system was in slack flow, regardless of filling location and tailings variability. This paper provides details of each of the three methods, including derivation, implementation, and comparison to operational data.

Keywords: *cemented paste backfill, underground mine, backfill plant, underground reticulation system, slack flow, pipe wear, paste operation, SCADA*

1 Introduction

1.1 General

Cemented paste backfill (CPB) is becoming increasingly common across underground mining operations as it provides cost-effective confinement and regional support, while simultaneously disposing of a potentially hazardous waste product – tailings. In addition, CPB adds value to a mining operation by permitting a greater extraction ratio of the orebody, fewer pillars/ribs of ore are left behind, and reducing the surface impact of the tailings storage facility (TSF).

CPB systems are typically more complex than the conventional backfill types, and as such design and operations of CPB systems come with complications. Primarily consisting of tailings material, typically accounting for 90 to 97% of the total solids in the CPB mix, CPB production is coupled to the mineral beneficiation plant. As such, paste production is directly influenced by mining and mineral processing operations. Consequently, changes in tailings mineralogy/ore type, particle size distribution (PSD), and solids concentration affect the performance of the paste plant and the CPB product, giving rise to variable rheology and strength performance of the CPB. The paper considers the effects of this variable rheology on the ability to deliver CPB from the paste plant to the stopes, where void filling occurs.

1.2 Reticulation system

A reticulation system is the network of pipes that hydraulically connects the paste plant, where paste is produced on the surface, to the underground stope, where the backfill is needed. CPB is delivered through this pipe network either by a positive displacement pump or under gravity flow. The pipe network consists of horizontal intra-level piping that is hung from the backs and follows underground tunnel routes and inter-level piping situated in steeply dipping boreholes. Reticulation networks can be large, with elevation changes of 1.5+ km and a total pipeline length of 5+ km. CPB flows through the reticulation system at a relatively slow line velocity, typically between 1 to 2 m/s. This is done to keep frictional losses manageable. It is possible to transport CPB at these slow speeds and over extensive distances in laminar flow as the risk of solids settlement and build-up is low due to the non-segregating properties of paste.

To operate a reticulation system successfully, control must be maintained over paste rheology to prevent over-pressurisation of pipes and to ensure the system has enough driving head (either from a pump or gravity) to deliver paste to the end of the network. The above problems occur when the paste is too ‘thick’ (lower water content – higher viscosity and yield stress) and highly resistant to flow. However, making paste too ‘thin’ (higher water content – lower viscosity and yield stress) can also be determinantal to the operation of a reticulation system. There are two key disadvantages of running thin paste. Firstly, the higher water content required to make the paste thinner reduces the strength of the cured paste, increasing the required binder dosage rate to achieve the target support, thus increasing the unit cost of backfilling. Secondly, the reticulation can have an excess of head energy as the frictional losses of the paste flow are insufficient to dissipate the head energy generated by elevation change. When operating with excess gravity head energy, a hydraulic phenomenon called slack flow occurs. This paper will aim to briefly define and discuss the effects of slack flow on the reticulation network but will primarily focus on methods to detect slack flow in real-time.

1.3 Slack flow

In a hydraulic system with excess gravity head energy, the system will find an equilibrium where the available head equals the frictional head loss. To achieve this, the system will operate with partially filled boreholes, see Figure 1, where the level in the borehole equals the friction head losses of the system downstream. Above this equilibrium point, negative gauge pressures partially vaporise the carrier fluid resulting in partial flow, where the pipe contains two fluid phases (liquid and gas/vapour). This section of partial flow, above the borehole equilibrium to the top of the borehole, is called the slack flow region. In this region, fluid flow is no longer slow and controlled, as the vaporised fluid provides a shear-free boundary between the pipe wall and the paste solids resulting in limited friction to paste flow. In some paste backfill systems, the borehole inclination is so steep that freefall of the paste material occurs. Increased pipe wear occurs in the freefall zone due to the high velocity of the abrasive paste solids. A second region of much greater wear occurs at the transition point between slack flow and the borehole equilibrium. High-velocity paste from the slack flow region impacts this full flow region, rapidly dissipating this kinetic energy as it slows back to 1 – 2 m/s. This impact results in loud pipe banging, one of the most characteristic features of slack flow. This sudden deceleration results in high transient stresses increasing the fatigue rate of the pipe within the borehole and immediately downstream. Also, as the gauge pressure becomes positive at this boundary, inertial cavitation occurs as the vaporised fluid bubbles collapse, further increasing the wear rate at the equilibrium point.

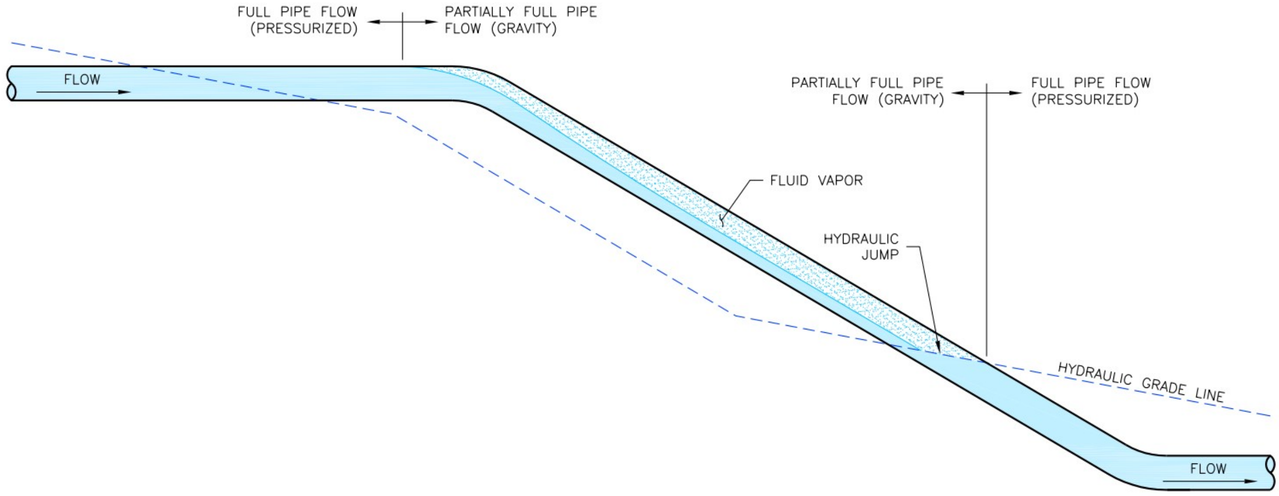

Figure 1 Illustration of slack flow within a borehole

Out of the two possibilities, running too thick or too thin, running too thin and allowing slack flow is often seen as the least damaging to production. This is because it is still possible to deliver CPB to the intended stope under slack flow, and systems can seemingly operate for extended periods of slack flow. Comparatively, Slack flow seems far less troublesome than making CPB too thick, blocking pipes and stopping backfilling. However, the effects of long-term slack flow operations can be equally disastrous for backfilling operations. Slack flow is the primary cause of premature borehole failure. It affects more extended boreholes more frequently as they have greater potential head energy and thus need more downstream frictional losses to maintain full flow. This downstream frictional loss requirement is frequently underestimated. Loss of a primary borehole due to slack flow can be sudden with little prior warning and will cripple an operation's backfilling capabilities for months. As such, every effort should be made to prevent long-term slack flow operation within reticulation systems to preserve the working life of boreholes.

2 Slack flow detection

Mitigating against slack flow is critical to extending the life of boreholes and ensuring continuous backfilling operations. However, detecting slack flow can be difficult. Each active borehole must be assessed individually, as there can be multiple instances of slack flow across the reticulation system. As such, a system should provide the paste plant operators real-time feedback on each borehole's status.

2.1 Hydraulic modelling

Hydraulic modelling, in the form of hydraulic grade line (HGL) plots, is a crucial tool used when designing a reticulation system. They help determine line pressures and required pipe ratings and identify slack flow regions. Figure 2 illustrates what slack flow looks like on an HGL. However, there are several drawbacks to HGL plots which prevent accurate real-time feedback and confine them almost exclusively to design purposes.

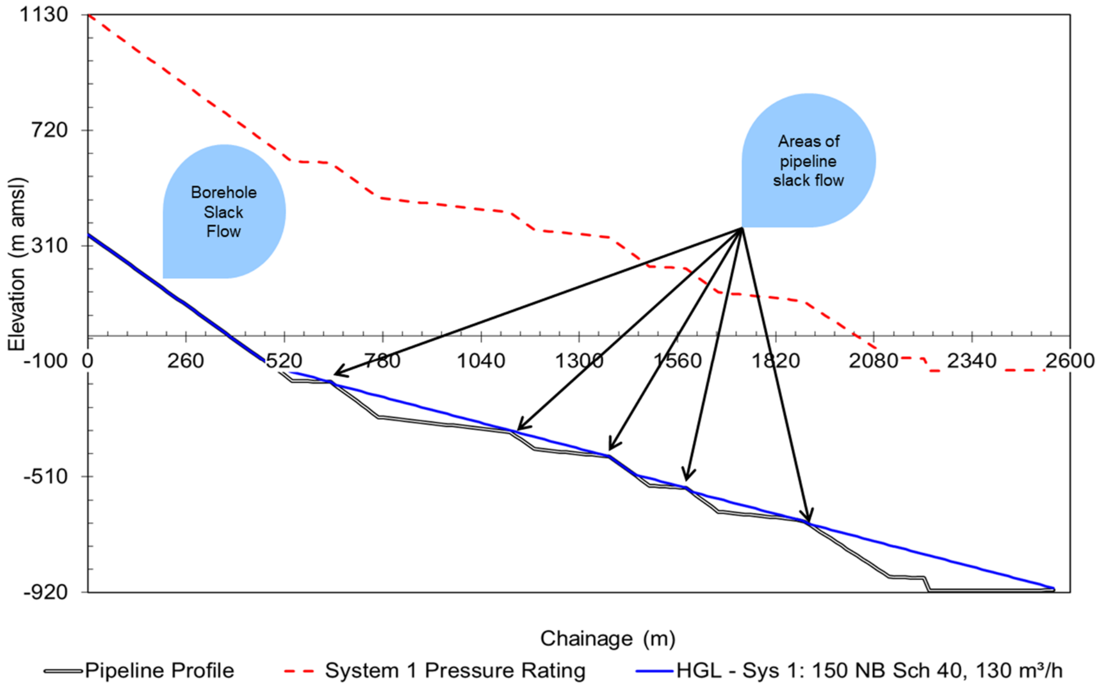

Figure 2 Hydraulic grade line plot with a system in slack flow

HGL plots assume consistent paste rheology across the entire active line. In reality, it could vary significantly with sections of thinner or thicker paste. This would result in discrepancies between the modelled line and actual pressures. Due to the considerable pipeline length of reticulation systems, only a minor rheology shift (±1% frictional losses) can be the difference between the full and slack flow.

HGL plots rely on 3D survey data of pipe routing, but it can be challenging to maintain an accurate database of pipe routings. Ad hoc pipe extensions or diversions are often omitted from the HGL analysis. Updating HGL routing data can be time-consuming and is infrequently carried out. As a result, there can be considerable differences between the HGL model and the actual underground routing.

HGL analysis can be used to develop an operating window for a specific stope, defining the lower limit of slack flow and the upper limit of pump capacity or over-pressurisation of piping. This operating window is defined by one of four sets of process parameters, which are dictated by the process controls and instrumentation available at the paste plant.

1. Slump (mm) and flowrate (m^3/h);
2. Solids concentration (%m) and flowrate (m^3/h);
3. Density (kg/m^3) and flowrate (m^3/h); and
4. Inline pressure loss gradient (kPa/m).

However, the first three assume a rheological correlation for a specific CPB material. If the material differs from this, the outputs from the HGL no longer provide realistic targets for the plant operator.

2.2 Underground PI detection

Paterson & Cooke have developed the following methods of assessing underground PIs, prompted by the need to provide real-time feedback to paste plant operators on the active borehole flow status, regardless of filling location and rheology of paste. These methods can be implemented in any reticulation system, with underground pressure monitoring, with calculations/analysis that can be incorporated into SCADA to provide a singular output to operators.

2.2.1 *Pump noise*

With pump-driven systems, it is possible to use the pump noise to determine the status of at least the first borehole from surface to underground and potentially all subsequent inter-level boreholes. This method relies on a characteristic phenomenon of positive displacement pumps, whereby the discharge pressure and flow rate follow a cyclical pattern. This pattern is most apparent with Simplex (single piston/diaphragm) and Duplex (twin chamber) pumps, for which, during the pump cycle, the discharge pressure and flow rate from these types of pumps reach zero for an instant in the pump cycle. The pressure and flow rate do not reach zero for dampened or Triplex (triple chamber) pumps. However, the cyclic nature is still apparent.

This cyclical pressure and flow rate is conveyed along the pipe. A 'pipe whip' can be observed with undampened single and double-action pump systems. Pipe whip occurs as the pumping pressure and flow rate fall to zero, but the paste within the pipe continues to flow forward due to inertia. This continued flow of paste results in a zone of negative gauge pressure, causing cavitation immediately downstream of the pump discharge; see Figure 3. This cavitation zone then propagates through the paste at the speed of sound (within the fluid medium). An audible 'whip crack' noise can be heard as the transient wave passes, and pipes flexing can also be observed.

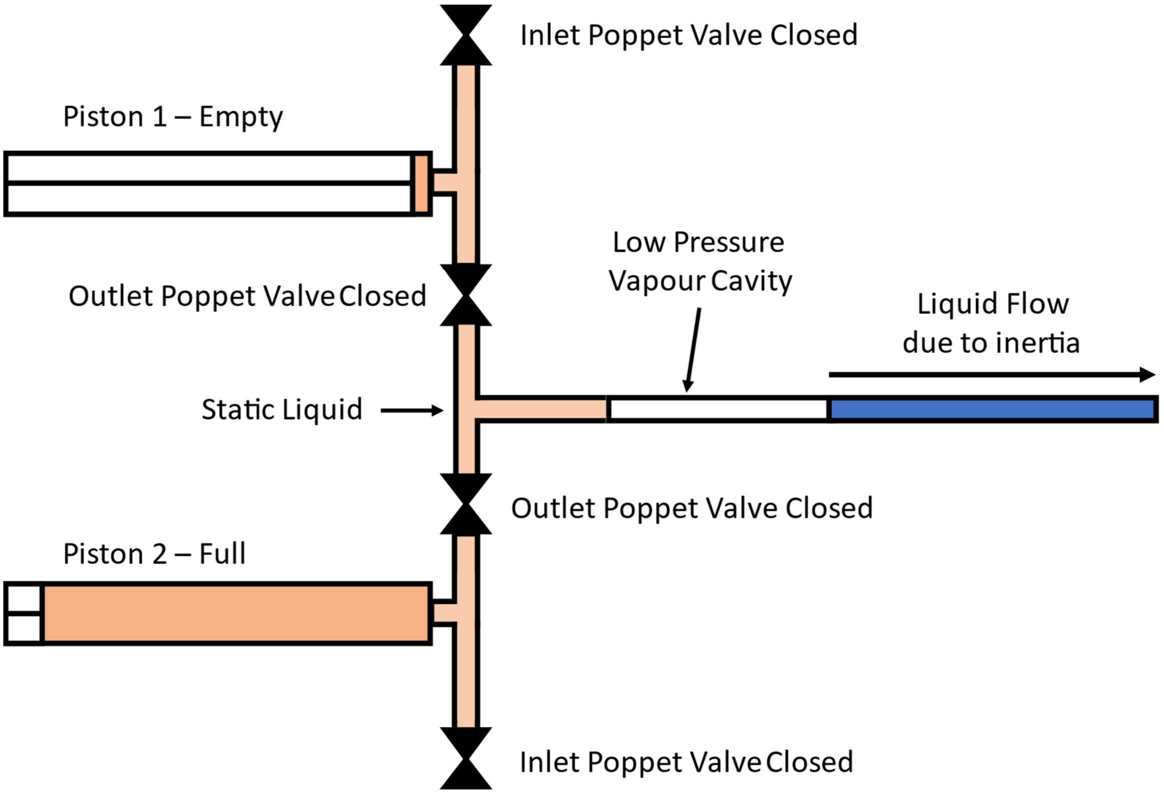

Figure 3 Pump noise generation – Transience

Pressure sensors downstream of the pump will be able to record these cyclical pressures given the following two requirements:

1. Data logging resolution is at least twice the pump cycle frequency, i.e. if a piston fills and discharges every 10 seconds (0.1 Hz), data logging must be at least every 5 seconds (0.2 Hz); and
2. There is a continuous hydraulic link between the PI and the pump discharge.

Upon reviewing PI data, if the pump noise can be detected, it can be assumed the system operates in full flow between the PI and the pump as the two are hydraulically coupled. However, if no pump noise is detected, there is a hydraulic break between the PI and the pump, indicating slack flow as the partial flow cannot transfer any pressure fluctuation due to the compressible nature of the vapour pocket, which attenuates any pressure waves, forming a hydraulic break.

2.2.2 Pump noise detection

Visual comparison between PI and pump discharge pressure graphs can be carried out to determine if pump noise is present at the specific PI. If present, evenly spaced spikes should be observed on both; see Figure 4. However, this method falls short of a comprehensive analysis tool. As more PIs are plotted, the display becomes increasingly cluttered and challenging to read. Furthermore, the more distant the PI from the pump, the lower amplitude of the detected pump noise, thus becoming increasingly harder to discern.

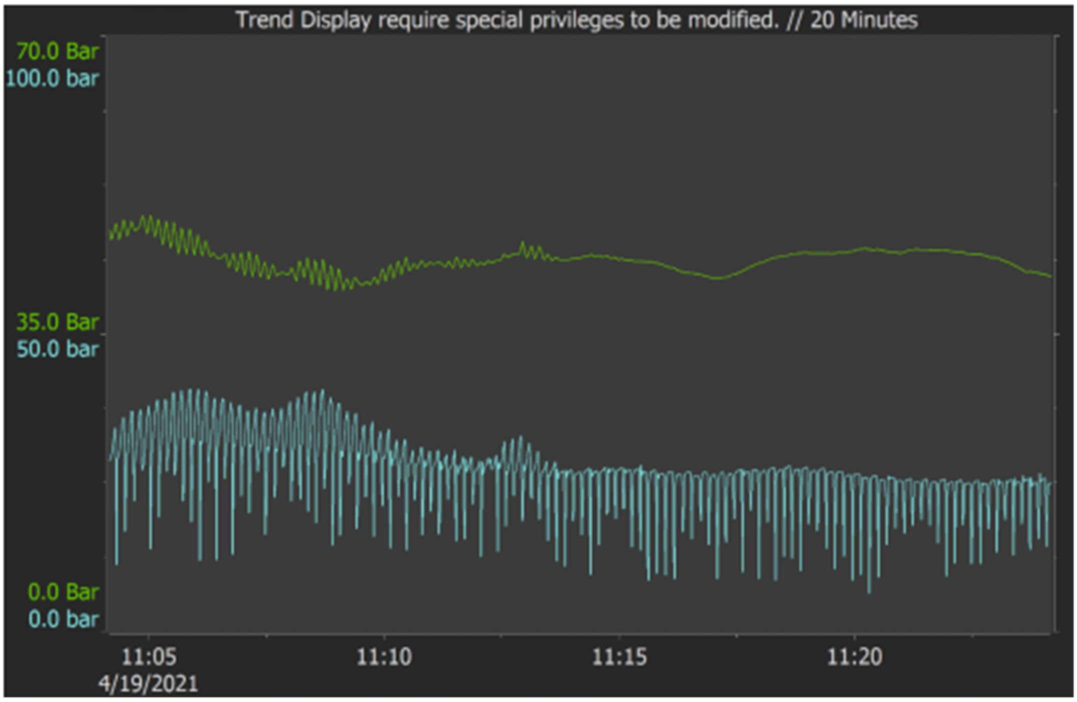

Figure 4 Pump noise detection moving from full flow to slack flow – Blue pump discharge pressure, green underground PI

A Fast Fourier Transform (FFT) can determine common frequencies between the pump discharge pressure and all active underground PIs. For this analysis method, the frequency of interest is the pump noise frequency (PNF). This noise has the same frequency as the piston stroke rate. This is a function of flow rate and pump design. Typically, this cycle time ranges from 10 to 30 s. For the case study discussed below, the stroke rate was ≈24 s or 0.042 Hz.

For more distant PIs (further from the pump), the relative FFT amplitude of PNF diminishes due to attenuation. The point is no longer visible on graphed data. Should the system be operating in full flow, extending the sample period of the FFT dataset will increase the FFT amplitude at the PNF relative to general noise frequencies FFT amplitudes, making detection feasible. This method can only be used to determine the first occurrence of slack flow, as any subsequent PIs downstream of the first occurrence of slack will also be devoid of pump noise.

For example, if three PIs are located across a reticulation network PI1, PI2, and PI3, each progressively further from the pump; see Figure 5. If slack flow occurs between PI1 and PI2, FFT analysis of the pressure data will reveal PNF in PI1 data and an absence in PI2 and PI3. However, this method does not determine the flow status between PI2 and PI3.

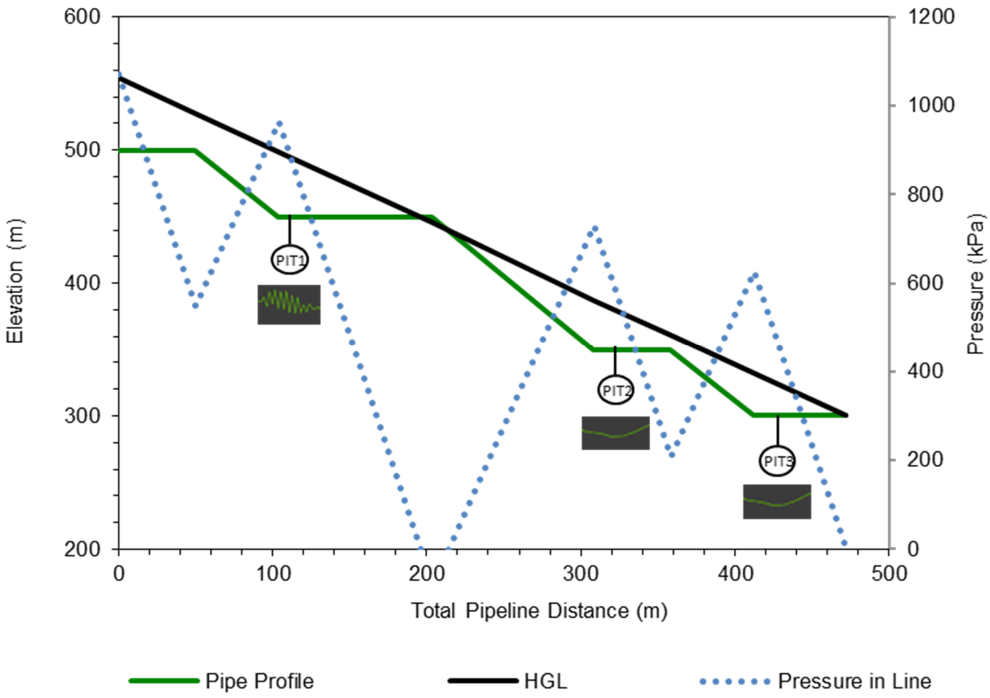

Figure 5 Hydraulic grade line plot – Slack flow between PI1 and PI2, no pump noise in both PI2 and PI3

Note that it may be possible to further improve this method by comparing each PI's complete frequency spectrum and the FFT amplitude of general noise. Should any two PIs be hydraulically coupled (full flow between them), general noise frequencies should be common between the two PIs, with FFT amplitudes following a similar distribution. This analysis method has the potential to confirm the status between any two PIs regardless of upstream processes or if the flow is carrying a known frequency (PNF), potentially permitting this method for gravity-fed paste systems. However, this form of analysis is beyond the scope of this paper since additional data is required to confirm its validity.

2.2.3 Slack flow envelope

A pair of PIs separated by a borehole can be used to verify the status of that borehole, regardless of upstream or downstream activities. However, this method relies on accurate survey data of the pipe routing between the two PIs, which cannot be used in areas where frequent modifications are made. Ideally, borehole pairs are either located immediately upstream and downstream of the borehole with no junctions between the PIs and the borehole or situated in a main borehole cascade where routes are fixed.

The analysis compares the average pressure loss gradient between the two PIs and the pressure loss gradient required to achieve 0 kPa gauge pressure at the top of the borehole. The system is in full flow when the average pressure loss gradient is less than the required. An estimate of the paste slurry density is required to undertake this analysis. Using the maximum possible density, the calculation will be conservative and overestimate incidences of slack flow. Equation 1 defines inequality that determines the borehole status, and 6 has been produced to illustrate this concept.

Using Equation 1, it is possible to develop a slack flow envelope by calculating P_2 for all the possible P_1 values at limiting slack flow equilibrium ($A_p = R_p$). This can then be plotted on a graph, dividing the plot into two zones: full flow to the right of the envelope and slack flow to the left. Data points can be quickly classified as slack or full flow by calculating which zone they fall in. This is done later in Figure 9.

Equation 1 represents the slack flow estimation slack flow envelope

$$Slack\ Flow\ when\ \frac{Average\ Pressure\ Loss\ Gradient\ (kPa/m)}{Required\ Pressure\ Loss\ Gradient\ (kPa/m)} = \frac{Ap}{Rp} > 1 \tag{1a}$$

$$where: Ap = \frac{P_1 + (h_1 - h_{bt})\rho g}{L_1} \tag{1b}$$

$$and: Rp = \frac{P_1 + \rho g(h_1 - h_2) - P_2}{L_1 + L_2 + L_b} \tag{1c}$$

$$L_1 = Chainage\ from\ PI\ 1\ to\ top\ of\ borehole\ (m) \tag{1d}$$

$$L_2 = Chainage\ from\ bottom\ of\ borehole\ to\ PI\ 2\ (m) \tag{1e}$$

$$L_b = Chainage\ of\ borehole\ (m) \tag{1f}$$

$$h_1 = Elevation\ of\ PI\ 1\ (m) \tag{1g}$$

$$h_2 = Elevation\ of\ PI\ 2\ (m) \tag{1h}$$

$$h_{bt} = Elevation\ of\ borehole\ top\ (m) \tag{1i}$$

$$P_1 = Gauge\ Pressure\ at\ PI\ 1\ (kPa) \tag{1j}$$

$$P_2 = Gauge\ Pressure\ at\ PI\ 2\ (kPa) \tag{1k}$$

$$\rho = Maximum\ paste\ slurry\ density\ (t/m^3) \tag{1l}$$

$$g = 9.81\ ms^{-2} \tag{1m}$$

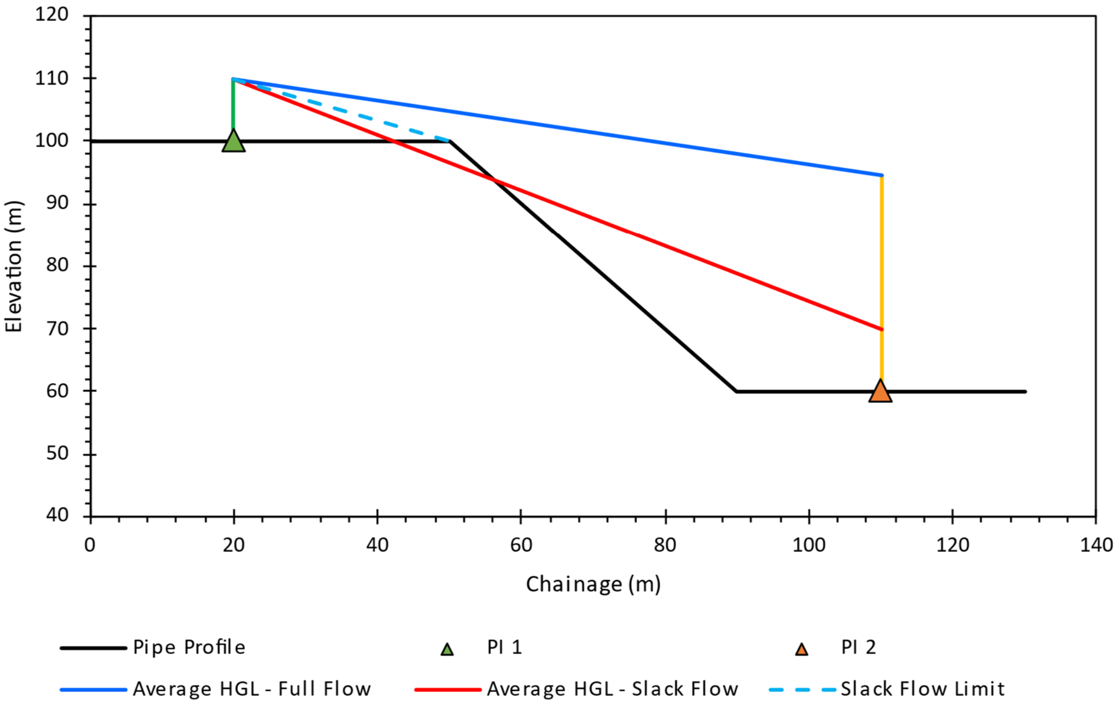

Figure 6 Borehole pair HGL plot highlighting slack flow and full flow

Note, this analysis assumes pressure losses within the horizontal piping are similar to the borehole pipe, i.e., boreholes and horizontal pipes are similar internal diameters and paste consistency does not vary between the two PIs.

2.2.4 PI pair projection

Any pair of PIs, with accurate distance measurements between them, can be used to determine the status of up or downstream boreholes. This is achieved by projecting the HGL between the two PIs forward or backwards to determine pressure within a borehole. Full flow is assumed if a borehole has an estimated top pressure of 0 kPa or greater. Equations 2 and 3 provide estimates of up and downstream top borehole pressures, respectively. Figure 7 provides a visualisation of this projection. Immediate downstream projections provide the least error via this method, as there is typically no change in pipe type nor a significant change in elevations. As a result, the assumptions required for this method become less influential.

Equation 2 represents an upstream borehole pressure estimation.

$$P_{ub} = P_1 + \rho g(h_1 - h_{bt}) + L_{ub}\left(\frac{P_1 - P_2 + \rho g(h_1 - h_2)}{L_{1-2}}\right) \tag{2a}$$

$$where: Slack\ Flow\ if\ P_{ub} < 0\ kPa \tag{2b}$$

$$P_{ub} = \ Upstream\ Top\ Borehole\ Pressure\ (kPa) \tag{2c}$$

Equation 3 represents a downstream borehole pressure estimation.

$$P_{db} = P_2 + \rho g(h_2 - h_{bt}) - L_{db}\left(\frac{P_1 - P_2 + \rho g(h_1 - h_2)}{L_{1-2}}\right) \tag{3a}$$

$$where: Slack\ Flow\ if\ P_{db} < 0\ kPa \tag{3b}$$

$$P_{db} = \ Downstream\ Top\ Borehole\ Pressure\ (kPa) \tag{3c}$$

$$P_1 = Gauge\ Pressure\ at\ PI\ 1\ (kPa) \tag{3d}$$

$$P_2 = Gauge\ Pressure\ at\ PI\ 2\ (kPa) \tag{3e}$$

$$h_1 = Elevation\ of\ PI\ 1\ (m) \tag{3f}$$

$$h_2 = Elevation\ of\ PI\ 2\ (m) \tag{3g}$$

$$h_{bt} = Elevation\ of\ borehole\ top\ (m) \tag{3h}$$

$$L_{ub} = Chainage\ from\ borehole\ top\ to\ PI\ 1\ (m) \tag{3i}$$

$$L_{db} = Chainage\ from\ PI\ 2\ to\ borehole\ top\ (m) \tag{3j}$$

$$L_{1-2} = Chainage\ from\ PI\ 1\ to\ PI\ 2\ (m) \tag{3k}$$

$$\rho = Maximum\ paste\ slurry\ density\ (t/m^3) \tag{3l}$$

$$g = 9.81\ ms^{-2} \tag{3m}$$

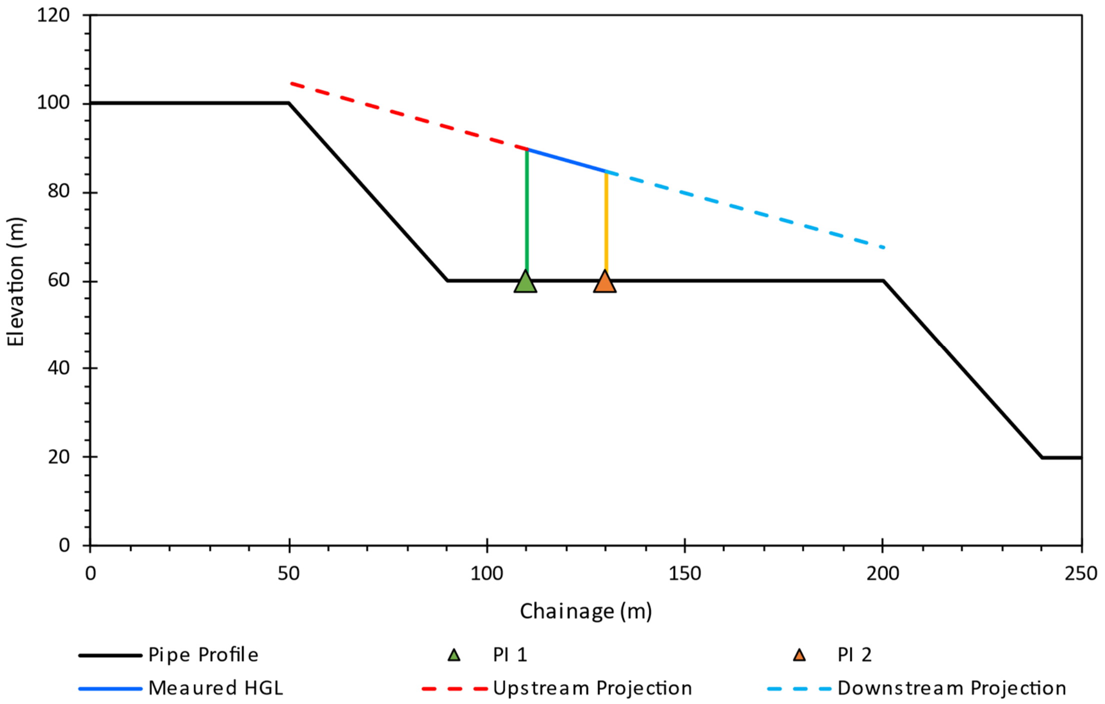

Figure 7 PI pair projection – Upstream project (dashed red line), downstream projection (dashed blue line)

Note, this analysis assumes pressure losses within the horizontal piping are similar to the borehole pipe, i.e., boreholes and horizontal pipes are similar internal diameters and paste consistency does not vary between the two PIs. Using two PIs to estimate the pressure at the top of all boreholes across the reticulation is possible. However, doing so encounters the same issues as HGL plots. As the distance increases, rheological variation becomes increasingly influential in borehole flow status calculation.

3 Operational case study data

These methods were developed during an extended visit to Boliden's Garpenberg mine, such that the status of the surface to Level 500 boreholes could be quickly checked for review purposes but also so that they could be implemented into the ABB system (SCADA system) to provide the operator immediate feedback as to the status of the boreholes.

The surface to Level 500 boreholes, lines 8300/8400/8500, posed a unique problem for Garpenberg as the historic pump discharge target of 15-20 bar no longer guaranteed full flow in the surface borehole. Previously filling operations took place solely in boreholes 8100/8200, the tops of which are located within the backfill plant with approximately 20 m of surface routing before going underground. As a result, any substantial pump pressure, >5 bar, guaranteed positive pressure at the top of the surface boreholes and thus full flow (in the first borehole at least). 8300/8400/8500 are located outside the backfill plant, with approximately 250 m of surface routing before being directed underground. Hydraulic modelling of the system, as illustrated in Figure 8, indicated that for some backfilling operations, all of this pump pressure was required to overcome the initial surface routing, and the pressure at the top of the borehole was less than 0 (gauge), implying the system was operating in slack flow.

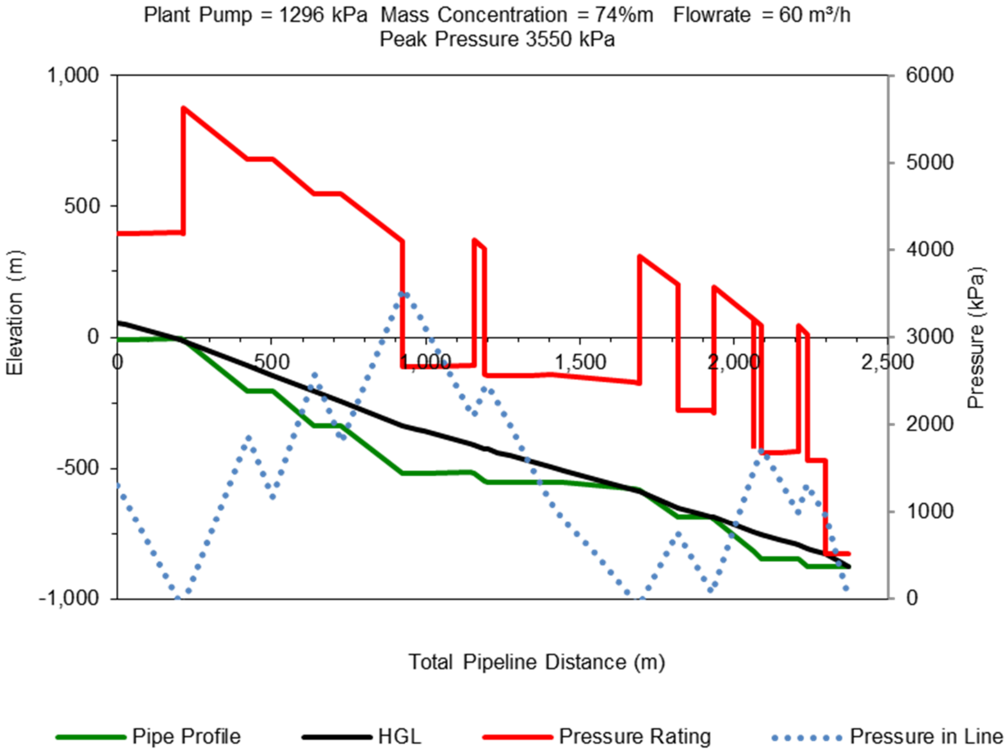

Figure 8 Hydraulic grade line plot line 8500 – 13 bar pump discharge pressure slack flow in the main borehole

After this initial discovery of slack flow via HGL analysis, boreholes 8400/8500 were inspected with an in-pipe camera. Significant wear was observed at a depth of 100 m within the borehole, and at a depth of 150 m, further passage was impossible as the pipe was entirely worn away, exposing the host rock. Garpenberg then requested P&C develop a method to determine the status of their boreholes to prevent additional premature borehole failures. Due to the complex nature of Garpenberg's reticulation system with multiple routes and distant orebodies, it was immediately apparent that a method to determine slack flow independent of routing would be required. Hence the aforementioned methods of PI data review.

3.1 Slack flow envelope

An HGL analysis could be carried out for each filling location to predict the occurrence of slack flow. These would dictate the mix design required and provide estimates of the line pressures across the whole system. However, this would be too time-consuming, with hundreds of individual routes modelled. As such, a simplified hydraulic analysis was undertaken to define the Slack Flow Envelope (defining the operating region where full is expected). This Slack Flow Envelope was defined using the simplistic analysis method described previously; see Equation 1. For each pump discharge pressure, the minimum borehole bottom pressure, sensor 8500PU PT2, required for $\text{Average}_{\text{pressure}} = \text{Required}_{\text{pressure}}$ (from Equation 1) was calculated. This high-level analysis produced a slack flow / full flow division, Figure 9, where pump and underground pressure pairs to the right of the line would be in full flow, and those to the left would be in slack flow. Operational data was then plotted on this chart, with the majority (73.3 %) of data points falling within the slack flow region, which aligns well with operational experience.

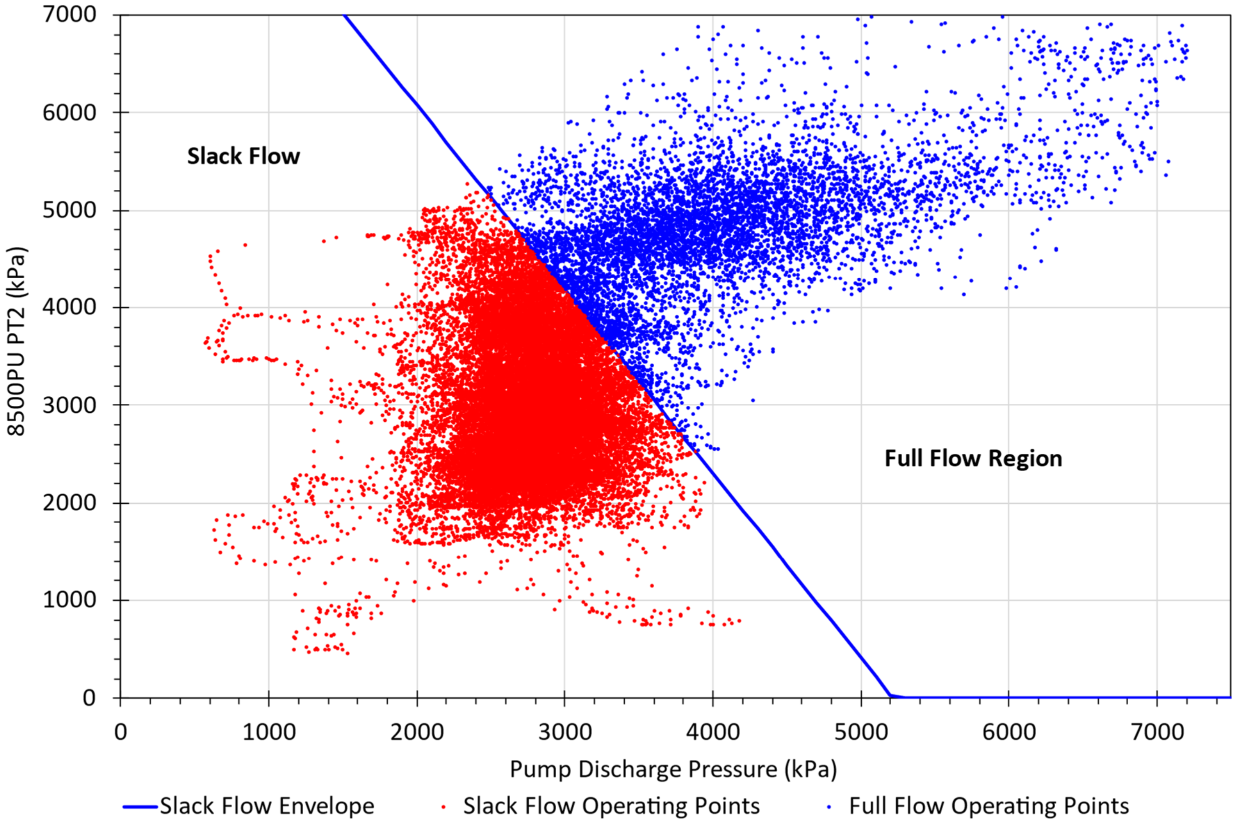

Figure 9 **Slack flow envelope – Full flow located to the right of the envelope**

3.2 PI pair projection

A set of three surface PIs, 8500PU PT100/101/102, situated on a straight section of pipe from the paste plant to the surface to 500 borehole, with a spacing of 50 m, were used to undertake projection analysis as described by Equation 3. In this case, the cut-off for full flow was determined by having an estimated maximum borehole pressure of 100 kPa or greater. The results of this analysis were mapped to the relevant pump and 8500PU PT2 pressures such that the results could be overlayed on the slack flow envelope produced in the previous section; see Figure 10. The results of this method form a less distinct pattern in terms of pump and PI pressures. However, there is still a clear pattern with most full flow points situated to the right of the envelope. The criterion of 100 kPa maximum borehole pressure is conservative, reflected in a higher ratio of slack flow at 79.1%.

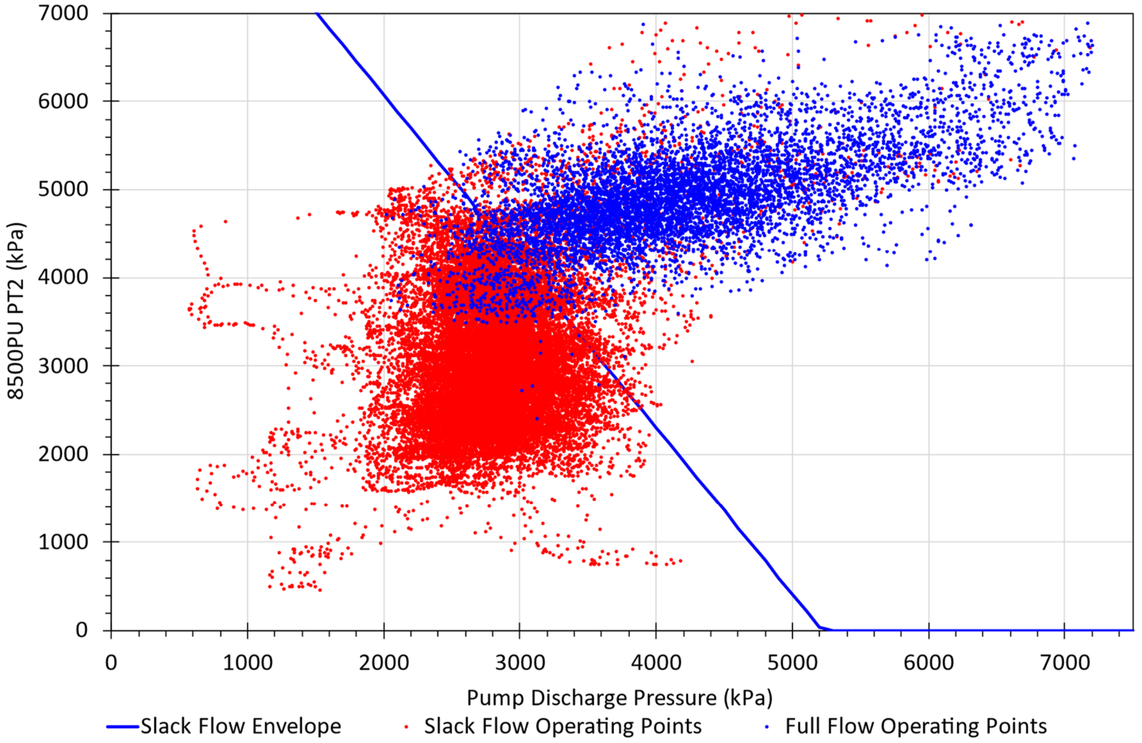

Figure 10 PI pair projection full and slack flow data points overalled on slack flow envelope

3.3 Pump noise detection

Pump noise detection analysis was also performed on the pump discharge pressure and 8500PU PT2 datasets. Analysis was initially carried out on the complete datasets to determine what range of frequencies would be of interest, i.e. range of PNF. Figure 11 and Figure 12 show the results of the FFT, including Hamming adjustment, of the pump discharge pressure and 8500PU PT2, respectively. The average PNF was calculated to be 0.042 Hz, with a pump cycle time of approximately 24 seconds. This frequency spike can also be seen in the 8500PU PT2 data, albeit less dominant.

To determine the flow status, blocks of data points were assessed individually. If the dominant frequency of the pump block data matches the dominant frequency in 8500PU PT2 block data, it is assumed the system was operating in full flow for that entire block duration. If dominant frequencies are not common, slack flow is assumed for the entire period. This assessment method can significantly improve by incorporating a 'rolling block'. However, sequential blocks are sufficient for this paper and proof of concept.

The block size was selected to be 32 data points as this is the smallest block size that provides sufficient frequency resolution to distinguish pump noise from general noise accurately. Table 1 provides a summary of the block size and the frequency resolution of the block.

Table 1 FFT block size and relevant frequency resolution

Parameter (units)	**Value**
Block Size	32
Block Period (s)	240
Sample Rate (Hz)	0.13
High Pass Filtered (Hz)	0.014
Average PNF (Hz)	0.042
PNF Standard Deviation (Hz)	0.0011
Frequency Resolution (Hz)	0.0041
Block Closest Frequency (Hz)	0.041

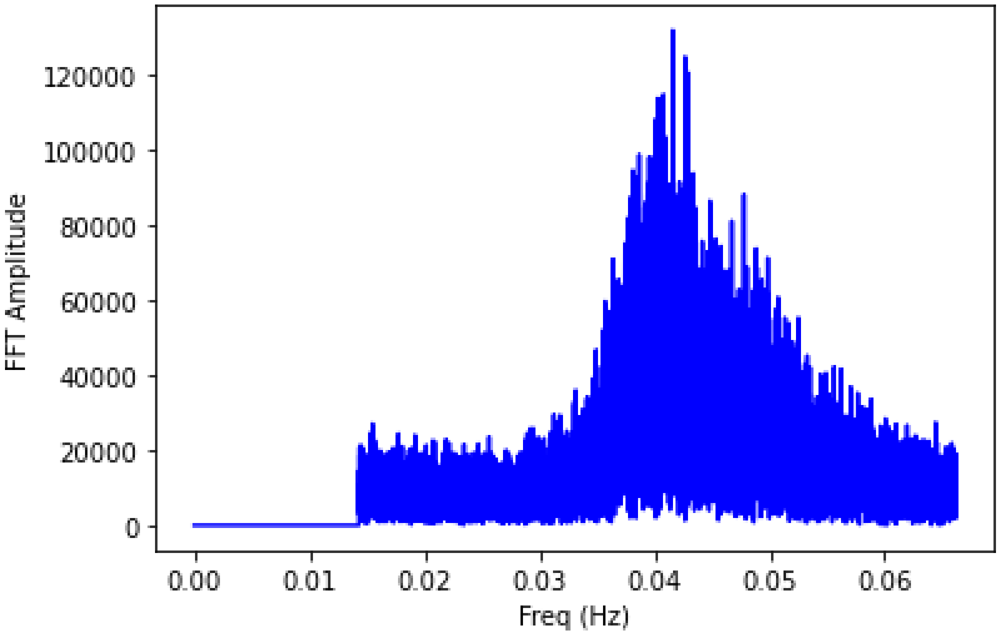

Figure 11 Pump discharge pressure FFT analysis results – Average frequency 0.042 Hz (stroke rate 23.6 seconds)

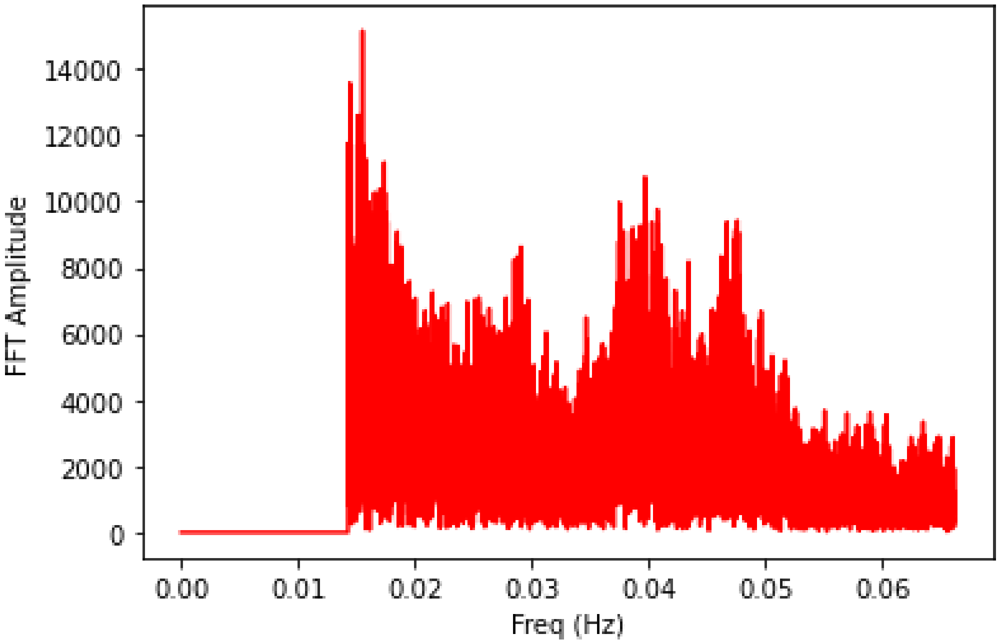

Figure 12 8500PU PT2 FFT analysis results – Slight spike around similar frequency as pump discharge

FFT analysis determined the system was operating in slack flow for 79.8% of the time, comparable to the result of projection analysis. Figure 13 shows the FFT results of slack and full flow incidences mapped to the slack flow envelope graph. Appendix A provides two examples of positive and negative PNF detection using the FFT analysis method.

The FFT results plot shows a similar pattern to the projection results plot, with no clear boundary between slack flow and full flow results (in terms of pump and PI pressures). However, the general pattern of most of the full flow points occurring to the right of the envelope persists. Notably, there is a group of points with low pump and PI pressures (less than 3000 kPa) identified as full flow. These were determined to be in slack flow by the other two methods. Further analysis identified these as artefacts from the block analysis method where block periods coincide with the transition from full flow to slack flow or vice versa.

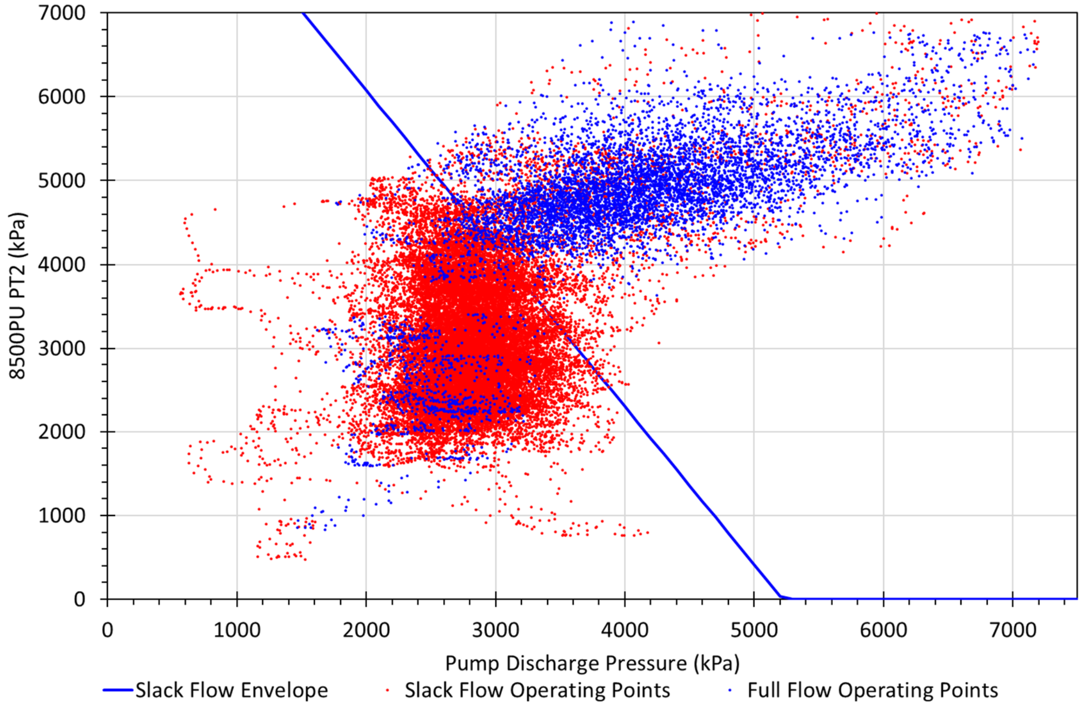

Figure 13 FFT full and slack flow results overlayed on slack flow envelope

3.4 Results comparison

The slack flow analysis results from the three different methods discussed in this paper are summarised below in Table 2. Between each method, there is significant overlap, with 83.7% of data points assigned the same flow status by all three methods; 69.0% slack, 14.6% full, and 16.3% mixed.

Table 2 Slack flow analysis results – Summary of different methods

Method	Slack flow (%)	Full flow (%)
Slack flow envelope	73.3%	26.7%
PI pair projection	79.1%	20.9%
Pump noise (FFT)	79.8%	20.2%

4 Discussion

Each method described in this paper can be implemented as a real-time solution to detect slack flow within a paste backfill reticulation system. Calculations are lightweight and can be easily programmed into a SCADA system. However, as there is significant overlap between each analysis method, there is not one preferred solution (all on par). Furthermore, each solution requires a different arrangement of PIs since such method selection depends on system design.

From the data within this paper, the FFT analysis is the most conservative method with the highest rate of slack flow incidents. As mentioned, the analysis method used in this paper is not optimal with block analysis classifying a group of potential different status points, all as either full or slack flow. However, the results presented in this paper should be considered more as a proof of concept, which does indeed validate this method, providing the same flow status as envelope analysis 87.2% of the time and projection analysis 88.9%. Further improvements that should be explored in the future include; higher resolution data, rolling block analysis to identify transition points and full spectrum analysis such that flow status can be determined without needing a known frequency carrier (PNF). A key benefit of FFT analysis is that no assumptions or details regarding the paste nor the reticulation are required to undertake this analysis.

Projection analysis was comparable to the FFT analysis regarding slack flow rate. The basis of this analysis method requires accurate survey data of the PI spacing and the pipe length to the top of the borehole. Additionally, it assumes the distance between the PIs and the borehole is short enough that paste rheology will not significantly differ. The larger the distance, the less reliable this method becomes (process variation becomes more significant).

Envelope analysis, for this case study, provided the lowest slack flow rate, albeit similar magnitude to the other two methods. However, this method relied on accurate survey data of the PI locations, pipe routing, and borehole length. In addition, this method assumed the pressure loss gradient was the same within the borehole as in the surface pipe, and the paste density was assumed to be 2000 kg/m^3. Each of these inputs and assumptions likely impacted the reliability of this method, hence the significant difference between this method and the other two.

Finally, paste backfill operations should include PIs across the entire reticulation system for monitoring line pressures to prevent over-pressurisation or blockage detection. They can also be essential tools to determine the flow status of boreholes. It is critical to know when slack flow occurs to mitigate future slack flow, reducing the risk premature borehole failures.

5 Conclusion

Envelope and project analysis methods discussed in the paper are an extension of the current hydraulic modelling method, considering the hydraulics of a localised area rather than the entire route from plant to stope. By localising the assessment region, the flow status of the borehole can be estimated regardless of upstream or downstream activities, making the calculations simpler and more flexible for operations with lots of filling locations.

The Fast Fourier Transform analysis method discussed in this paper provides an alternative approach to determining flow status that is not reliant on the assumption of paste rheological properties. However, further investigation is required to develop a generalised application.

APPENDIX A: Examples of FFT Outputs

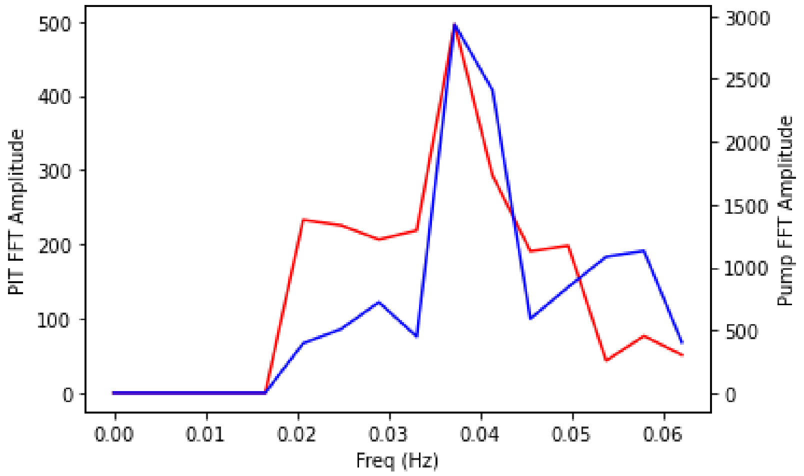

Figure 14 Example 1 of positive pump noise detection – PI FFT in red, pump FFT in blue

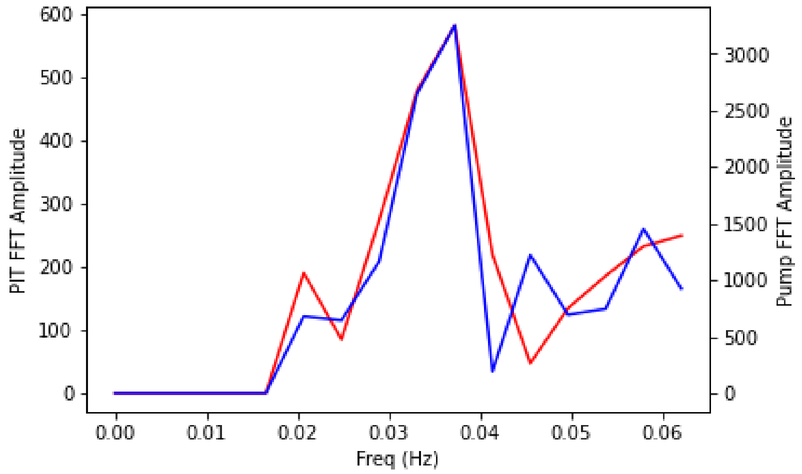

Figure 15 Example 2 of positive pump noise detection – PI FFT in red, pump FFT in blue

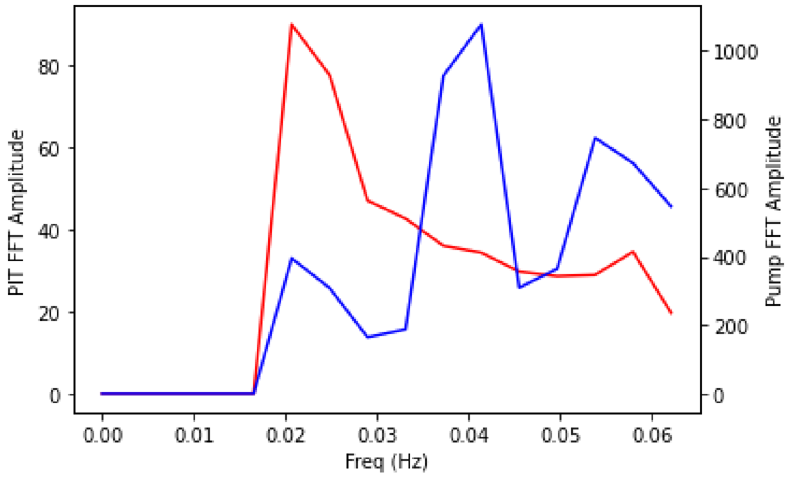

Figure 16 Example of 1 of negative pump noise detection – PI FFT in red, pump FFT in blue

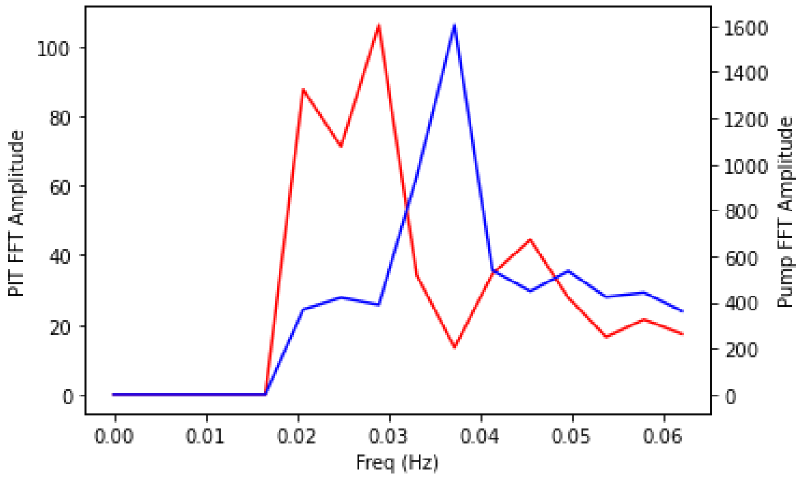

Figure 17 Example 2 of negative pump noise detection – PI FFT in red, pump FFT in blue