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Throttling a cemented paste backfill underground distribution system

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Abstract

Throttling the flow in a pipeline increases the upstream pressure, allowing for the pressure profile of the pipeline to be "raised" over a problematic area of the reticulation network, such as an area where freefall occurs.

This paper will outline the design and implementation of such a throttling system for a cemented paste backfill reticulation system, including a design discussion on how chokes are used to throttle the flow and the calculation of the theoretical pressure drop. The implementation section provides insights into how an underground choke station was installed and the commissioning process. Furthermore, this section discusses the sustainability of the choke station, including how it should operate, and how the station will be utilised in the future.

Keywords: *laminar flow, choke, underground, backfill, reticulation, delivery, hydraulics*

1 Introduction

The purpose of an underground distribution system (UDS) is to deliver the best quality cemented paste backfill (CPB) possible from a plant located on the surface to the to-be-filled underground void with the least effort. A high-quality CPB is homogeneous with predictable rheology and backfill strength gain and is produced at the highest practical density to achieve the target strength with the minimum amount of binder. The primary contributor to the pipeline friction loss is the yield stress, which increases exponentially with the CPB density. Ideally, the UDS should be designed to accommodate high CPB densities. However, this is not always possible due to constraints related to the geometry of the orebodies and development, lack of backfill development capital, availability and longevity of development, backfill rheology, change in design, etc.

Due to these design constraints, it may be necessary to retrofit or modify the UDS to optimise its performance. This paper will discuss how the design constraints mentioned above usually manifest in reticulation issues and will discuss some methods that can be used to mitigate these issues. The particular focus of this paper is the relatively novel mitigation method of installing choke orifices. This focus will include a discussion of a choke and how multiple chokes can be incorporated into a choking station. The discussion will then move to a case study examining the implementation of a choke station at Newmont Tanami Operation's Dead Bullock Soak (DBS) underground (UG) mine. This case study will look at the design, installation, and commission of the 620L choke station. The final component of the case study will be a review of the choke station operation, including some of the issues that arose and how they were addressed.

2 Delivering a cemented paste backfill

A UDS is a pipeline used to deliver the backfill from the surface to the excavated stope. The flow regime will be either turbulent or laminar, depending on the backfill type. Under ideal operating conditions, CPB is transported in the laminar flow regime (compared to a hydraulic or sand fill transported in the turbulent regime). This pipeline consists of vertical interlevel boreholes and lateral pipeline sections. Many factors, including the location of the surface plant to the UG development, the shape of the orebody and subsequent mine design, etc., dictate the pipeline's location.

Figure 1 contains a plot showing the life of mine (LOM) UDS for four different mines. Each UDS was normalised to its starting point, allowing for easy comparison:

- The blue UDS has a long horizontal section and a steep vertical component. This is because the mine is shallow, and access to the top of the orebody was impossible.
- The orange UDS has a very long surface delivery borehole and a shallow dipping UG component. The orebody, in this case, dips at a continuous angle. The upper portion of the mine had been excavated using a method that did not require cemented backfill. However, the mining method changed with depth and required cemented fill. Therefore, the surface backfill plant was built above where the cemented fill was needed.
- The black/green and red UDS are examples of how the UDS is modified as new ore bodies are discovered. Long lateral runs usually distinguish these modifications in directions perpendicular to the usual overall trend of the main UDS.

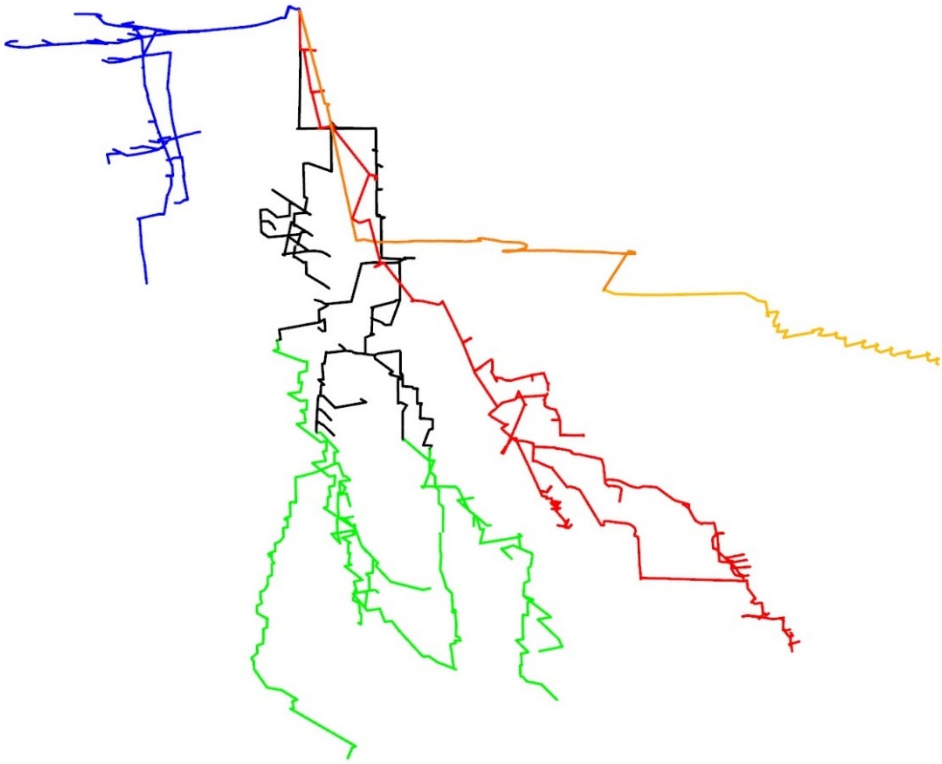

Figure 1 An isometric plot comparing the geometric differences of four UDSs

An easier way of visualising the UDS is to compress its 3D nature into a 2D plot of the pipeline profile showing reticulation chainage versus depth. The black line in Figure 2 shows this compression for part of the black/green UDS from Figure 1 (which is the UDS for DBS).

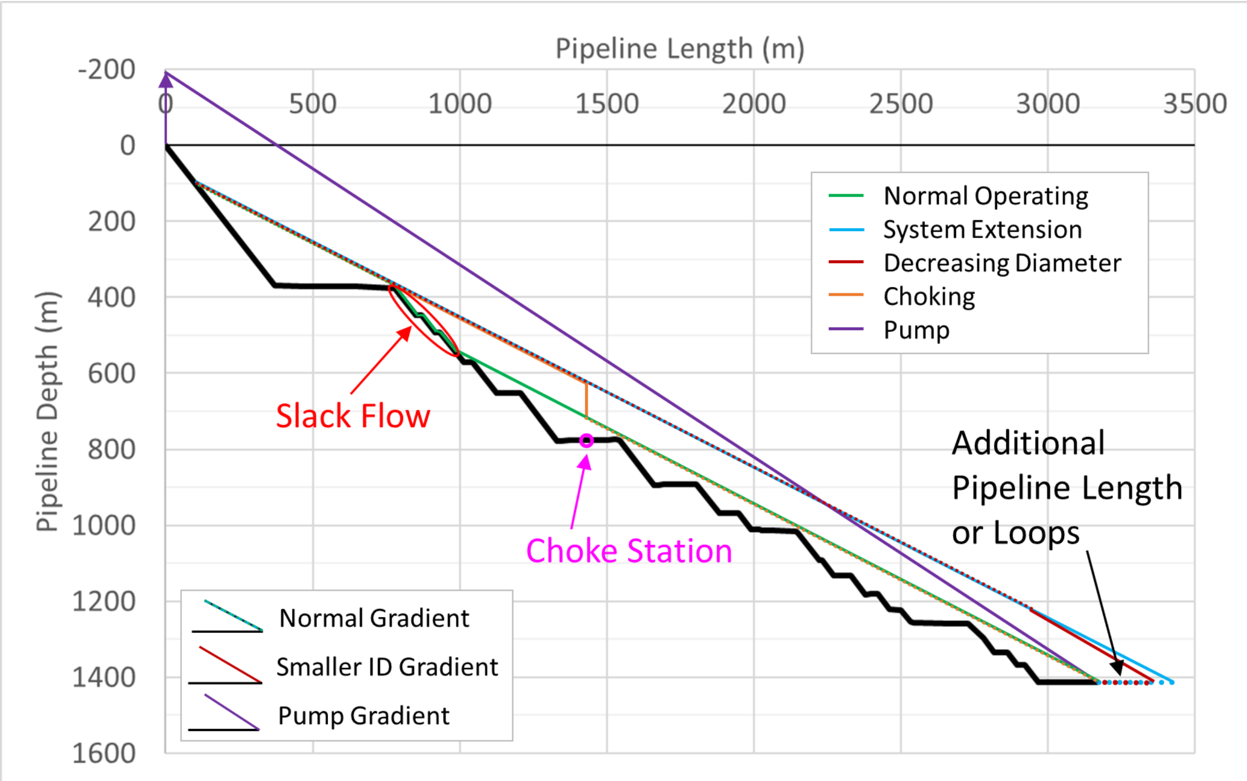

Figure 2 A hydraulic grade line plot showing how a UDS can be modified to account for adverse UDS geometries

A common method for analysing the performance of a particular UDS configuration is to determine its steady-state hydraulic grade line (HGL). The hydraulic grade line shows the variation of pressure (expressed in terms of head of CPB along the pipeline). The slope of the HGL is indicative of the friction loss gradient (m/m) of the system (i.e., the amount of head required to move the CPB one metre along the pipeline). The steeper the HGL, the higher the friction loss gradient, while the shallower the HGL, the lower the gradient. The yield stress primarily contributes to the pipeline friction loss gradient, increasing density exponentially. Thus, at the same flow rate through the same pipe size, material at a higher density will have a steeper HGL than the same material at a lower density.

There are several HGLs shown in Figure 2, but the one that is of interest is the normal operating HGL (green line). The UDS at DBS is fed using gravity, which means that the system can only be powered by the available gravity head (i.e., if the green HGL were to reach the surface, the system would have fully utilised the available head). It is generally not possible to design a gravity system to operate in full flow (i.e., no slack flow or freefall within the surface borehole) due to flux within the system caused by changes in the rheology of the CPB. Tailings inconsistencies usually cause these rheology changes. The design process at DBS allows for 100 m of freefall, which enables the system to accommodate this flux. For all scenarios considered below, the aim is to maintain this buffer.

Slack flow conditions arise when the absolute pressure inside a pipeline falls below the liquid or slurry vapour pressure. Typically, this occurs downstream of a local high point along a pipeline route. In a slack flow condition, the slurry will flow with a free surface in the slack flow condition (i.e., open channel or launder flow). If the pipeline slope is steeper than the hydraulic gradient when the pipeline is flowing in slack flow, the slurry will accelerate unit it reaches a velocity such that the friction losses equal the pipeline slope. This velocity may be significantly higher than the full flow rate resulting in rapid erosion of the pipeline invert. Where the slurry from the slack flow section flows into the downstream pressure piping, it will entrain vapour bubbles in the pressurised flow. This results in cavitation with the potential for erosion damage in this section of the pipeline.

The green HGL drops below the pipeline profile at the end of the first UG lateral transfer, resulting in slack flow along this piping section, highlighted by the red circle. As stated above, this significantly increases velocity through the pipeline resulting in significantly increased wear rates. There is cavitation, high turbulence, and vibration at the interface, where the slack flow returns to full flow. This localised release of energy can damage the inside of the pipeline, and the vibration can cause fatigue (particularly the supports) that may require frequent repairs.

The HGL drops below the pipeline profile at the end of the first UG lateral transfer because the pipeline profile downstream of that point is steeper than the HGL. The reason for this is the relatively steep ore body development underground, in combination with the relatively long lateral section of piping on the first UG level, which spans most of the distance between the CPB plant on the surface and the ore body. There are several ways to rectify this situation by modifying the HGLs, as shown in Figure 2.

Note that the HGLs in Figure 2 were only modified to the point where slack flow is removed from the system (i.e., the HGLs touch the pipeline trace at the top of the first underground borehole). This means that the gradient of the gravity-driven HGLs, with the same pipeline ID, are the same. However, an operating margin would be introduced in an actual operating situation to keep the UDS from entering a slack flow regime, as shown in Figure 3.

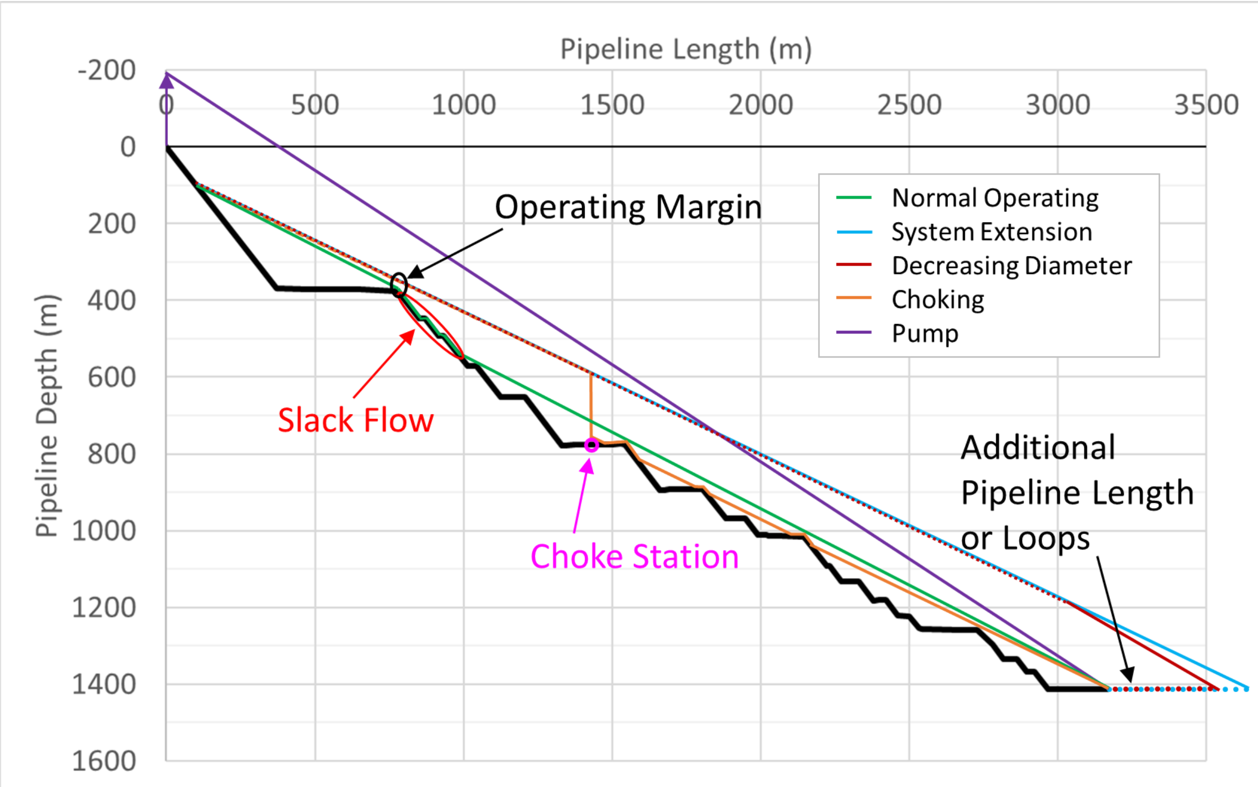

Figure 3 A hydraulic grade line plot showing how a UDS can be modified to account for adverse UDS geometries

The most common solution is to extend the length of the UDS by installing additional pipe lengths before the CPB enters the stope (generally referred to as loops). The light blue HGL illustrates this in Figures 2 and 3. The pipe is made longer than the minimum required to achieve an operating margin for avoiding slack flow, and due to the fixed gravity head available, the UDS must operate with a shallower HGL slope. This shallower slope is achieved by operating at a lower density, requiring more binder for similar strengths. It also requires additional operational effort to install the loops.

Another common method is to utilise a smaller diameter pipe on the last lateral transfer (dark red HGL). The smaller diameter pipe will have a higher friction loss gradient (i.e., steeper HGL slope), which is why the dark red HGL in Figures 2 and 3 has two different slopes. This allows a shorter (or potentially no) loop to be installed. The smaller diameter pipe provides more than the minimum required head loss to achieve an operating margin for avoiding slack flow. Due to the fixed gravity head available, the UDS must operate at a lower density, similar to the solution above.

An alternative to the above methods is to increase the head available by adding a high-pressure slurry pump to the surface plant (purple HGL). The additional head allows the system to operate with a steeper HGL and consequently at higher densities (requiring less binder to achieve similar strengths). The steeper HGL is above the pipeline profile at all points allowing slack flow to be avoided. This method does not require additional operational effort underground (modifying pipe lengths and sizes). However, it does require the capital investment of procuring, installing, and commissioning the pump and the downtime related to that.

The method discussed further in this paper is the installation of a throttling choke station at an intermediate underground level, shown by the orange HGL in Figures 2 and 3. The choke station provides a step-change rise in the HGL, allowing slack flow in the problematic upstream piping section to be avoided. In order to achieve an operating margin for avoiding slack flow, more choking is provided than is always necessary. With the fixed gravity head available, the UDS must operate with a shallower HGL slope at a lower density. This shallower slope is achieved by operating at a lower density, requiring more binder for similar strengths. The choke station generally does not require additional operational effort underground once it has been set to an appropriate throttling level. This setup can be performed while the plant runs, resulting in less downtime. However, the shallower HGL and step-change may impact the downstream behaviour of the UDS, as shown by the orange HGL in Figure 3.

Prior to the choke station, it was typical for DBS to use pipeline extensions and less typically to use reduced-diameter piping. However, this required dedicating significant UG operator time to install. Ultimately, this will be addressed by installing a positive displacement pump to upgrade the DBS backfill system. However, a shorter-term solution was needed to improve the performance of the UDS before the upgrade could be brought online. Therefore, the decision was made to install a choke station at DBS.

2.2 What is a choke?

Typically, a choke is an intentionally significant decrease in pipe diameter that causes the flow within a pipeline to be constricted. As the fluid (in this case, CPB) is forced through the orifice, there is an initial slight increase in pressure upstream of the orifice. However, for the fluid to go through the orifice, the fluid's velocity must increase, and the fluid pressure must decrease. The point of maximum convergence (the vena contracta) occurs just downstream of the constriction. This is where the fluid's maximum velocity and minimum pressure occur. After this point, the fluid's velocity starts to decrease, and the pressure starts to increase. However, due to local energy losses, the pipeline pressure does not return to its previous pressure and stabilises at this lower pressure. Two pressure drops are associated with a choke: the total pressure drop across the choke (ΔP in Figure 4) and the permanent or effective pressure drop (Δw in Figure 4), which is the difference between the choke's upstream and downstream pressures.

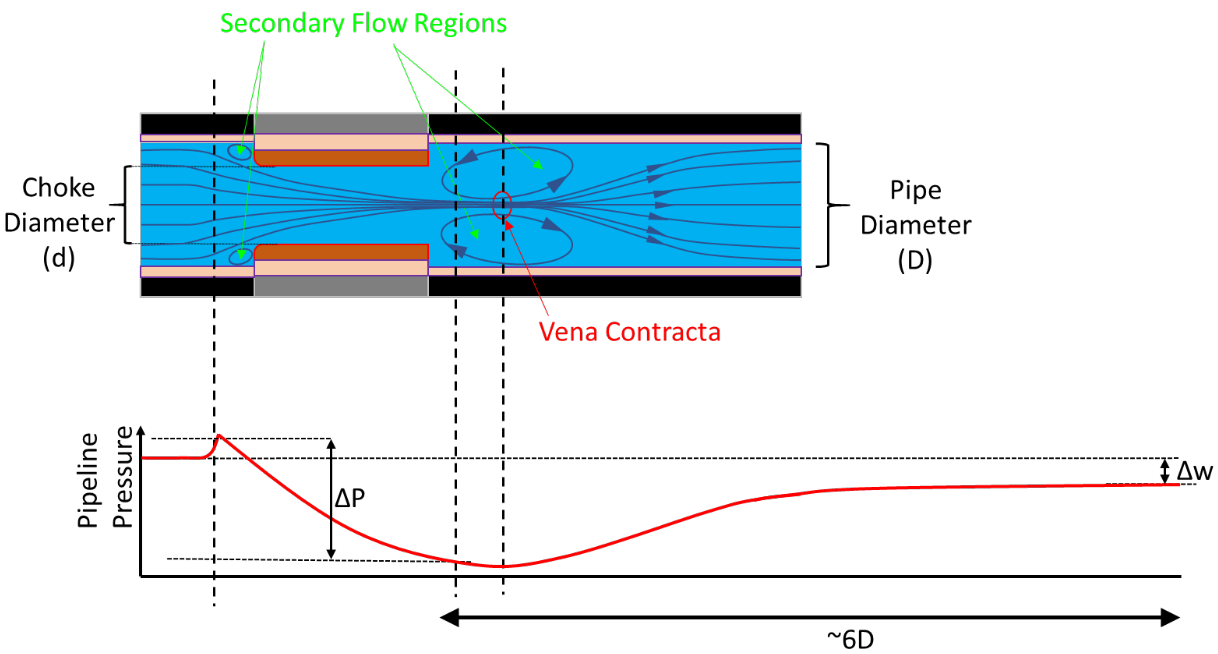

Figure 4 A schematic showing the different zones within a choke (upper plot) and how this relates to the pressure changes within the choke.

Ultimately, determining Δw is required. The ratio between the effective and total pressure drop can be approximated by the below equation (AFNOR 2003):

$$\frac{\Delta w}{\Delta P} \approx 1 - \beta^{1.9} \tag{1}$$

where:

β is the ratio between the pipe and choke internal diameters (d/D). In DBS's case, the pipe and choke IDs are 0.12 m and 0.06 m, respectively, making β equal to 0.5.

However, this requires the ΔP to be estimated. This can be calculated using Equation 2 and solving for the total pressure drop (assuming full pipe flow through the choke) (ISO 2003). Note that Equation 2 is valid for a range of Reynold's numbers. The Reynold's number for this CPB was outside of this range. Despite this, Equation 2 was used for calculating the theoretical mass flow rates.

$$q_m = \frac{C}{\sqrt{1-\beta^4}} \varepsilon \frac{\pi}{4} d^2 \sqrt{2\Delta P \rho_1} \tag{2}$$

where:

q_m is the mass flow rate (kg/s)

C is coefficient of discharge (usually around 0.61 for a β = 0.5)

ε is the expansibility factor (1 for incompressible fluids)

ρ_1 is the fluid density (kg/m³)

A choke station allows for multiple chokes to be added in series, allowing for greater control over the amount of pressure drop. Note this equation shows that the ΔP (and, hence, the Δw) is sensitive to both the density of the CPB and the plant throughput. This sensitivity is explored in the plot shown in Figure 5. The head loss per choke is shown for four throughputs converted into mass flow rates over DBS CPB's normal density range (coloured markers). This indicates that changes in throughput significantly impact a choke's head loss more than the density.

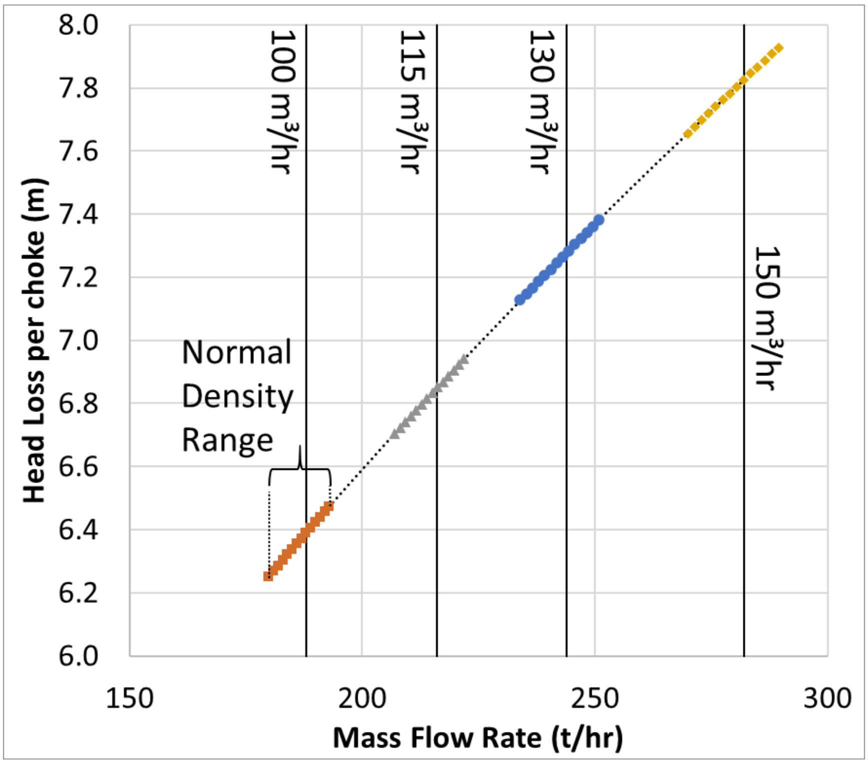

Figure 5 A plot showing the relationship between mass flow rate and head loss per choke. Note that the mass flow combines the CPB's density and the system's throughput.

Based on these equations and using DBS's usual CPB densities and throughputs, the effective pressure drop per choke is around 7.1-7.3 m of CPB head.

3 Implementing a choking station

As mentioned, a choke station is a series of chokes allowing multiple chokes to be installed and removed as necessary.

3.1 Design

Early in the design stages, it was decided that the station should include space for 20 chokes. This was more than what normal use dictated, but given a lack of data on laminar flow choking, it was decided that having additional choking power was preferable to underestimating.

Finding a location for the choke station was also vital, as it needed to be far enough down the line to improve operation in as much upstream piping as possible and sufficient to cover the different UDS branches. These constraints led to the Callie line choke station being installed on the 620L. This placed the station above the lower and mid-level branches, and an unutilised cuddy could be easily modified into the station. Figure 6 shows the location of the choke station on the 620L as well as a more detailed schematic of the choke station itself.

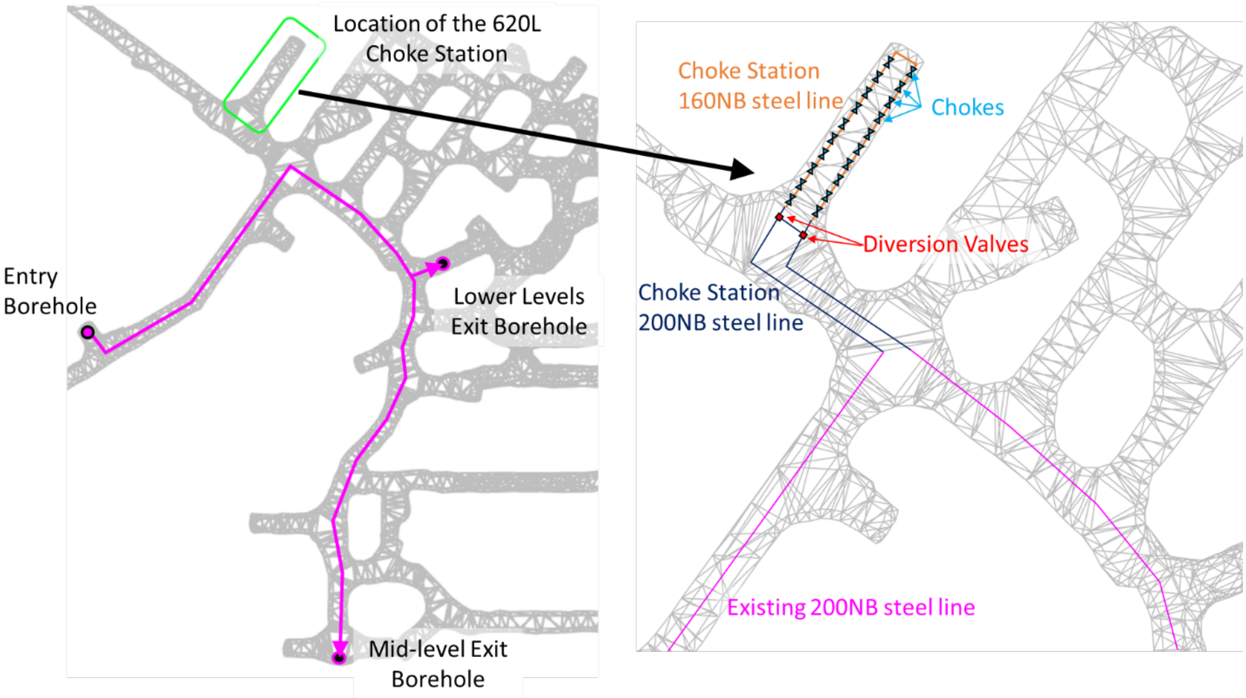

Figure 6 Two plots showing the location of the choke station on the 620L (LHS) and a more detailed view of how the choke station was installed (RHS)

The choke station was designed to be simple, and the different components are shown in the photograph in Figure 7. A spacer separated each choke, and each spacer was clamped to a steel and concrete pedestal mounted to the drive's floor. The spacer and chokes were connected via a quick-release coupling. Both the chokes and spacers were lined with a wear-resistant ceramic coating. Additionally, choke blanks were manufactured to allow the number of chokes to be changed and were lined with a ceramic coating.

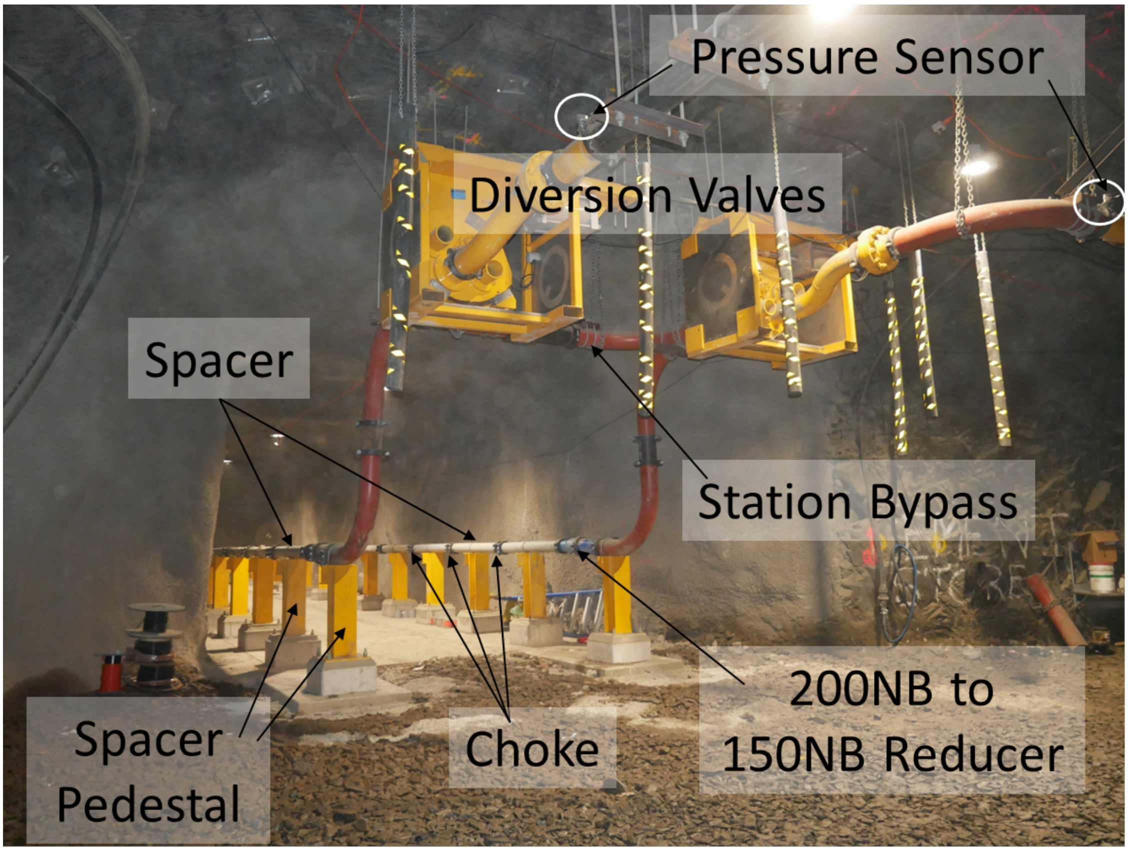

Figure 7 An annotated photograph of the installed 620L choke station

The choke station loop is entered and exited through an upstream and downstream diversion valve. This allows the choke station to be bypassed if not required. The valves can also isolate the choke station from the line to make flushing easier in case of a blockage.

The initial station piping design utilised DBS's standard 200 NB schedule 80 steel pipe. However, building the station around a 150 NB steel pipe was easier and cheaper. In order to make the chokes easier to install and remove, the line was brought from the drive backs down to waist height.

Instrumentation consisted of pipeline pressure sensors upstream and downstream of both diversion valves. This allowed the pressure before and after the choke station to be monitored and confirmed that the bypass was being used.

3.2 Commissioning

Commissioning involved updating the design procedure and ensuring the physical station worked. The first involved updating the operation's hydraulic model to account for the choke station. This involved determining how to represent the pressure losses due to the choke station in the model.

These losses are due to the increased pipe lengths (both 200 NB and 150 NB) and any losses across the diversion valves. The length of the 150 NB was assumed to be consistent (i.e., this length doesn't change). The theoretical choking pressure loss per choke was determined using Equations 1 and 2. The total pressure drop across the station was determined by multiplying the theoretical pressure drop over a choke by the number of chokes. Figure 8 shows the application in the model, with the 150 NB pipe divided into pre- and post-station sections and the choke pressure drop component located within this length.

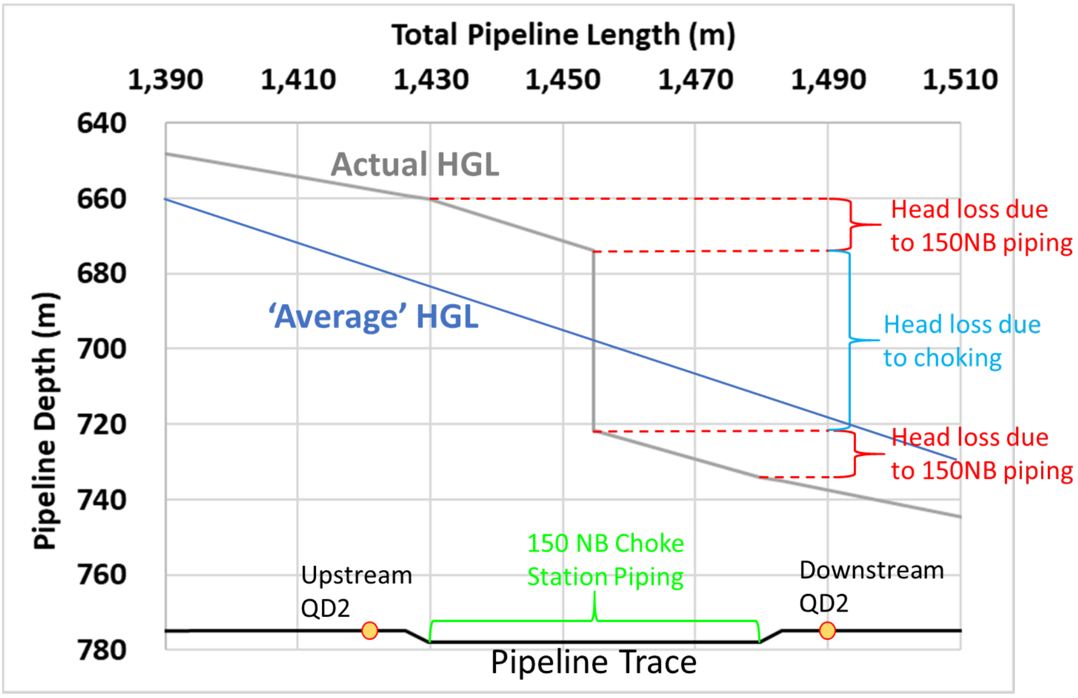

Figure 8 A HGL plot showing how the choke station was implemented into the hydraulic model

A total of three stopes were used to commission the 620L choke station: 133A, 139C, and 145C. Multiple runs were made to each to establish a non-choked baseline and determine how increasing the number of chokes impacted the pipeline pressures.

The results of these runs are shown in Figure 9 and are shown as HGL plots. The in-situ instrumentation determined the pipeline pressures, and the HGL plots were obtained using the operation's hydraulic model. The red line (in all the plots) shows the non-choke HGL. From this, it is apparent that UDS operated in slack flow conditions when running to all three stopes. In particular, the slack flow area is located in the upper portions of the mine. The main reason is that the CPB density is too low, demonstrated by free fall lengths greater than the expected 100 m. The other HGL lines (green, purple, and cyan) show the instrumentation/model results of installing two, three, or five chokes. These plots all indicate that the choke station does 'jump' the pressure higher. Note that the common operating procedure for the DBS BP is maintaining pressure at the first 1020 pressure sensor. This is particularly apparent in the 133A and 145C plots, where the 1020L pressures are essentially the same, but the choked instrumentation results show the 'jumped' pressure at the 620L (at approximately 1,500 m of pipeline length). These commissioning tests were performed using only a few of the chokes to reduce the risk of blockage. By operating through more of the chokes, it would be possible to further reduce or avoid slack flow in the upstream inter-level boreholes.

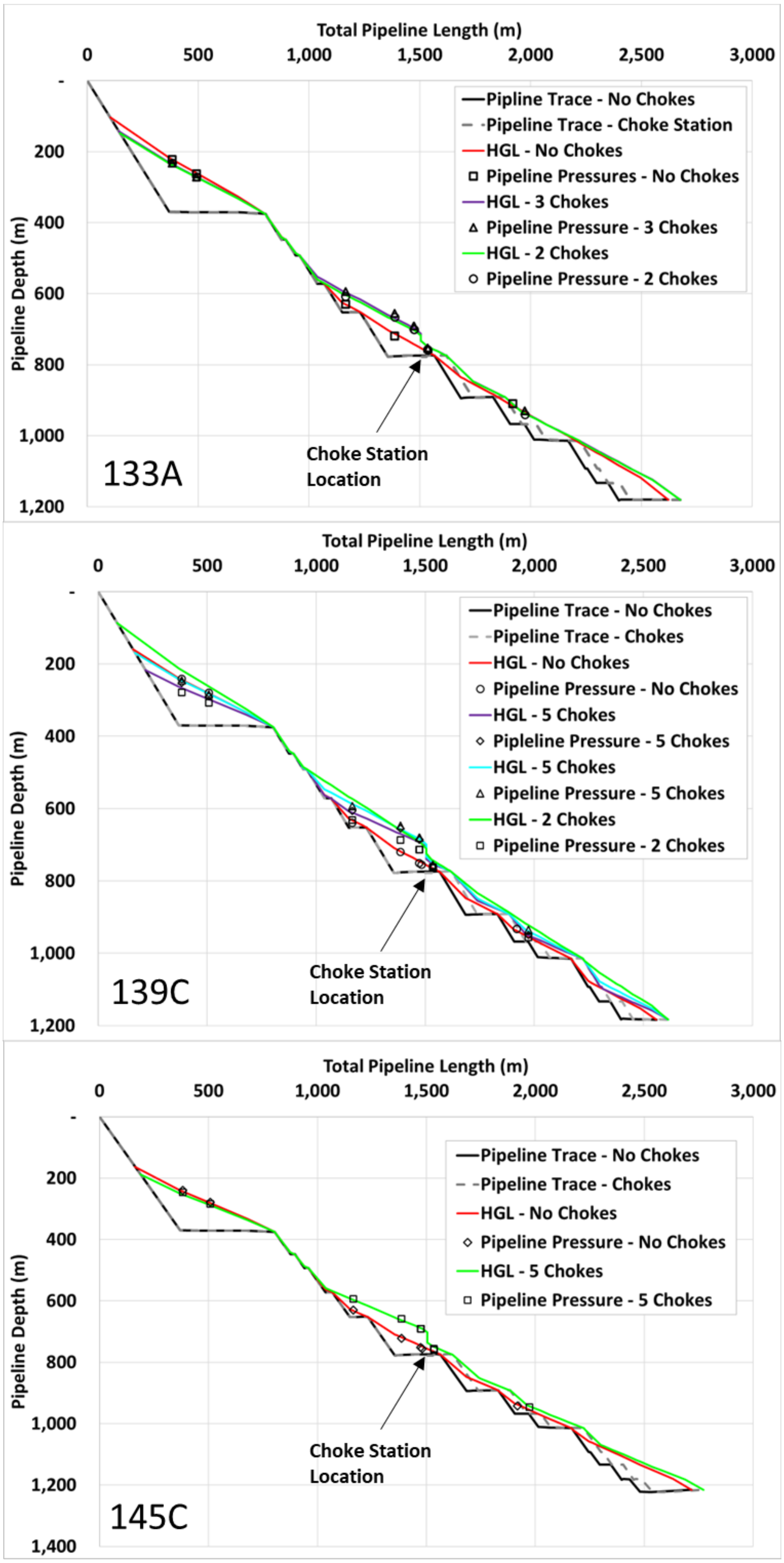

Figure 9 HGL plots for the three stopes used for the commissioning process.

3.2.1 Model correlation discussion

Model correlation is challenging given that the model is steady state (i.e., constant flow rate and density) while the UDS system is dynamic. To this end, the current procedure at DBS is to obtain the historic pressure trends and then identify relatively stable periods to take pressure measurements. This data can then be plotted with the pressure profile generated by the model (the left-hand plot of Figure 10 illustrates an example). Ideally, the pipeline pressure data would correlate to onsite rheological measurements, but this is generally unavailable. However, once obtained, a 'best-fit' model line can be determined, and this best-fit HGL can be plotted (right-hand side plot of Figure 10).

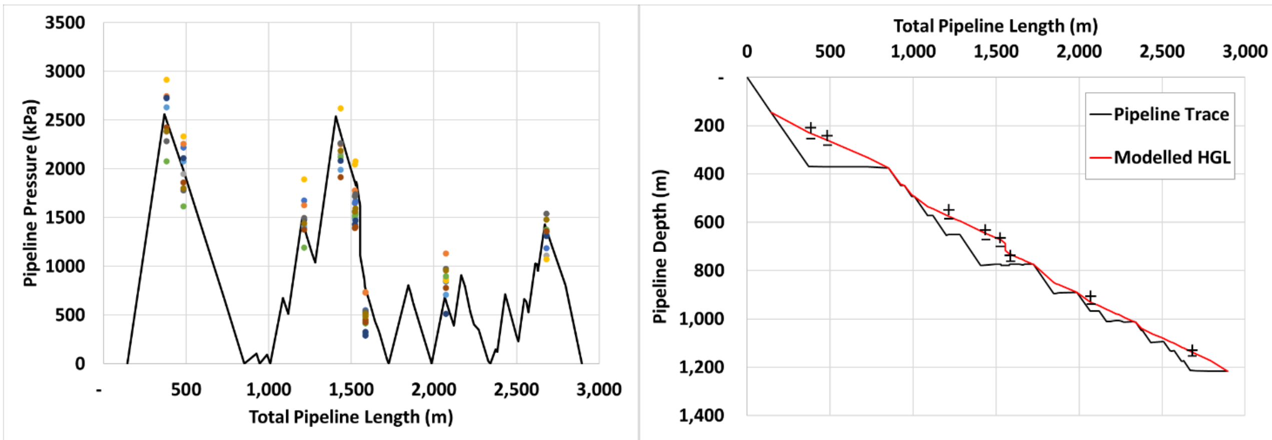

Figure 10 An example showing how pressure data obtained from the UDS pressure sensors can be correlated with the hydraulic model

This methodology was used during the commissioning period. However, the run times were limited as changing the number of chokes was necessary. As part of the commissioning, two parameters were compared: the pressure gradient on the 1020L and the head loss across a choke.

Table 1 shows the pressure gradient results from the commissioning. In general, this demonstrates a good correlation between the model and the instrumentation pressures. Using the pressure gradient to establish a correlation is useful if limited data is available (i.e., no density, per cent solids, or rheological measurements).

Table 1 A chart comparing the pressure gradient values obtained from the UDS pipeline pressure instruments during commissioning and the hydraulic model

Stope	Instrumentation pressure gradient (kPa/m)	Model pressure gradient (kPa/m)	Difference
133A	5.9	6.5	-0.6
133A	5.7	5.9	-0.2
133A	5.8	5.7	0.1
139C	4.2	4.3	-0.1
139C	5.7	5.5	0.2
139C	5.4	4.6	0.8
139C	5.6	5.4	0.2
145C	5.7	5.5	0.2
145C	5.7	5.1	0.6

Table 2 shows the measured and calculated head loss across a choke. This data shows less correlation and leads to a change in the DBS reticulation model where the user could enter a manual pressure drop value instead of the calculated value. However, it was found that there was a better correlation during analysis conducted outside of the correlation period. For the example in Figure 10, the average head loss across a choke was 7.8 m, and the calculated head loss was 7.2 m.

Table 2 A chart comparing the pressure drop across a choke obtained from the UDS pipeline pressure instruments during commissioning and the theoretical calculations

Stope	Number of chokes	Head loss calculated from instrumentation (m of CPB)	Theoretical head loss (m of CPB)
133A	3	11	6.7
133A	2	9	7
139C	2	15	6.9
139C	5	10	6.9
139C	5	10	6.9
142C	5	9	6.8

3.2.2 Commissioning comments

It was found that the choke station performed as designed in that it achieved a significant pressure drop in a short amount of space. It was found, initially, that the measured head loss across a choke was higher than the calculated head loss. However, this difference has decreased with additional use, possibly due to a 'wearing in' period.

The correlation between the updated choking model and instrumentation data was deemed sufficient to use the model for pour design purposes. A feature was added to the model to allow the user to either use the calculated head loss across a choke value or manually input this value.

4 Operating a choking station

The 620L choke station has now been operational for over a year, and this section will discuss some of the operational issues that have appeared.

4.1 Operational misconceptions and constraints

A choke station is designed to do one thing, which involves a significant change in pressure over a very short distance. However, it is only a mechanical change to the system and does not remove the typical operating constraints of a gravity-powered UDS. There will still be fluctuations in the system, particularly if the tailings feed is inconsistent. To this end, using a choke station will not remove the requirement of having a freefall zone within the surface delivery borehole. However, controlling the borehole level fluctuations would be easier depending on how the UDS operates.

Operating a choke station will require some decrease in CPB density to achieve an operating margin for avoiding slack flow. This will require the binder content of the CPB to be increased (to maintain the necessary CPB strength in the stope). However, this decrease in CPB density does have an advantage (beyond reducing slack flow above the choke station). Mainly this decrease in density also reduced the sensitivity of the CPB, as it takes a larger change in water content at lower CPB densities to enact the same amount of change at higher CPB densities (as shown in Figure 5).

Additionally, it is possible to change the system's flow, which, coupled with the density change, can affect the amount of the pressure drop across the choke (also shown in Figure 5). Theoretically, this can give a large amount of control over the system. However, this was not the outcome, as the throughput of a plant is usually kept at a maximum due to schedule constraints.

4.2 Downstream considerations

Due to the limited gravity head available, and to achieve an operating margin for avoiding slack flow, running through the choke station requires the UDS to operate at a lower density (requiring more binder to achieve similar strengths) and with a shallower HGL slope.

The shallower HGL slope is not of concern upstream of the choke station, as the step-change rise in the HGL allows slack flow in the problematic upstream piping sections to be avoided. However, the shallower HGL slope does result in the downstream piping being more prone to slack flow if the pipeline profile slope is steeper than the HGL slope. Figure 11 illustrates an example of this (along with the orange HGL in Figure 3).

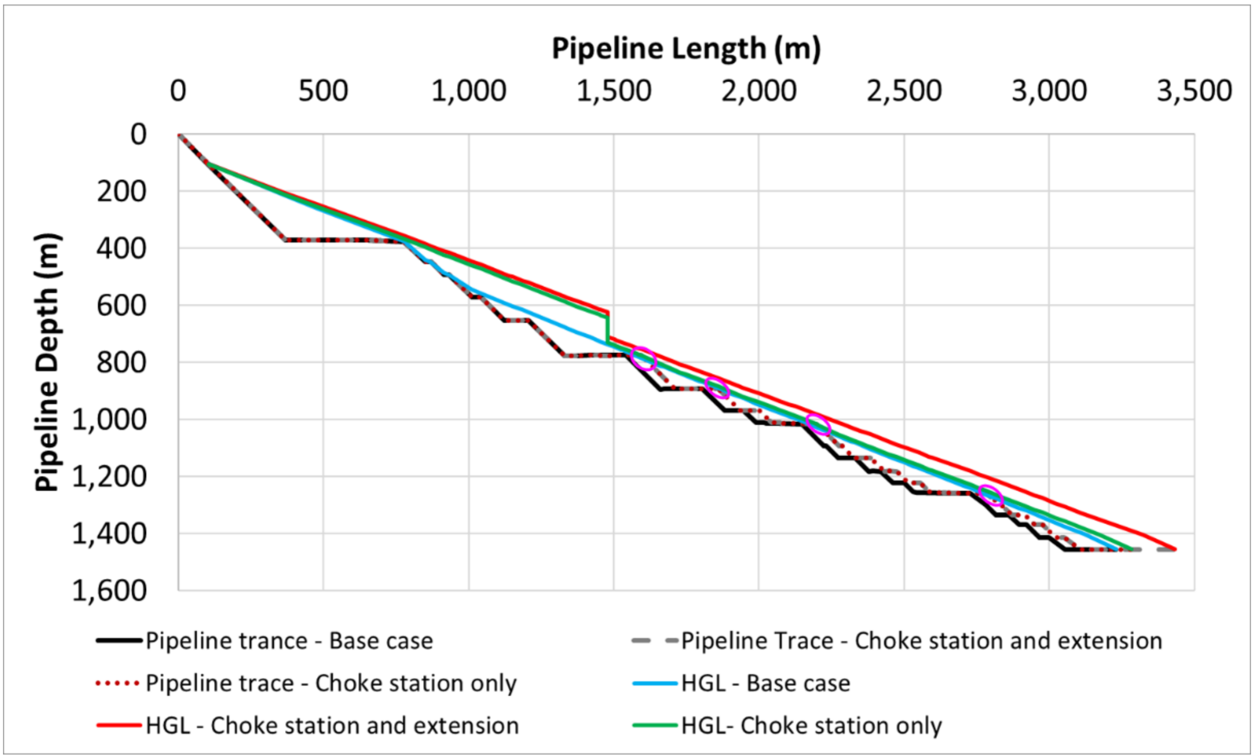

Figure 11 An HGL plot showing how using a mid-UDS choke station can improve the upstream conditions but worsen the downstream conditions and how this can be rectified.

The light blue HGL corresponds to the black pipeline trace. In this case, slack flow occurs in the upper portions of the UDS. There are also some areas of concern below the choke station. Choking the flow will allow the pressure to be jumped over the problematic upper areas (green HGL and dotted red line), which now causes slack flow in several lower boreholes (magenta circles). It is necessary to add an extension to the end of the reticulation network (in this case, it was an additional 100 m) to prevent this (red HGL and dashed grey line).

4.3 Running to multiple stopes

It is typical practice at DBS to have several stopes available to receive paste at any given time. This allows for a constant CPB placement rate if pouring into a particular stope needs to be paused (plug curing, level check, etc.). This means that the line needs to be switched between stopes. Each stope will have a unique UDS configuration, so the number of required chokes will differ. However, given the speed at which these switches need to occur, the number of chokes cannot be adjusted.

This led to a 'best for most' design philosophy where the number of chokes stayed the same for every stope. This meant the number of chokes remained low (usually less than eight), and the station was bypassed more frequently.

4.4 Ceramic performance

The chokes, the choke blanks, and the spacers were lined with wear-resistant ceramic material. For this installation, two different types of ceramic coatings were used. The chokes were manufactured with a higher grade of ceramic coating, while the spacers and choke blanks used a lower grade. This was done primarily to save costs.

However, it became apparent that the lower ceramic level was more susceptible to damage when being moved to set up the choke station and during choke station operation. Figure 12 contains two photographs. The LHS photograph was taken during a wear inspection, showing little wear or cracking. The RHS photograph shows a spacer pipe section taken after installation. The ceramic has cracked and delaminated from the steel pipe. The broken sections were replaced with spares before use, but similar damage happened during operation. Note the issue appears to be delamination from the steel, allowing the ceramic to crack. This issue was rectified by replacing the spacer and blank ceramic with a higher coating grade.

Figure 12 Two photographs showing the appearance of a choke during a routine wear inspection (RHS) and the ceramic in one of the spacers after installation

4.5 Blockages

One of the issues with a choke station is that material that would otherwise pass through the nominal pipe size may be caught within the reduced diameter at the choke. For example, one major blockage occurred when a piece of the surface delivery borehole ceramic lining came loose and was lodged within a choke. This caused a relatively instantaneous blockage. As a result, the pressure on the 620L pressure sensor increased by 7,000 kPa over about 5 minutes. Figure 13 shows an HGL line plot showing how the line was running before the blockage (red line) and the instrumentation values after the blockage (blue diamonds). The dashed purple line shows an estimated HGL for the pressure in the line during the blockage.

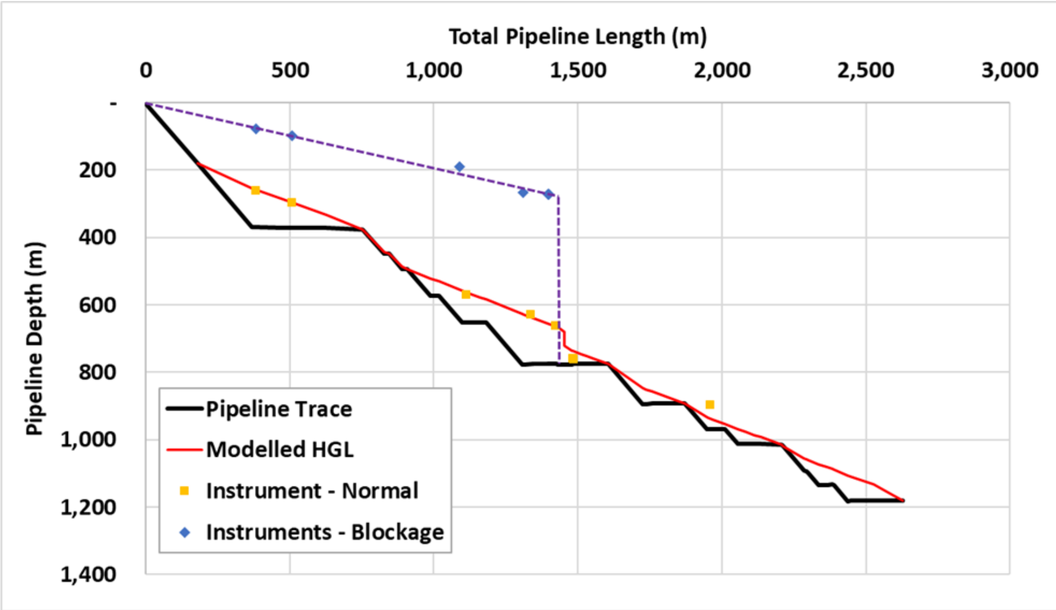

Figure 13 A HGL plot showing the pre- and post-blockage pressure profile as determined from the pipeline pressure sensors

The blockage was cleared by cascading dump valves to the dump station, bypassing the choke station, and clearing the rest of the line. However, the choke station then needed to be manually cleaned. The photographs in Figure 14 show the blocked line downstream of the first diversion valve and the clearing of that section of pipe. The chokes, blanks, and spacers were then cleaned by hand. Due to this, restrictions were placed on when the choke station could be utilised, limiting it to when a 100% steel surface delivery borehole was used.

Figure 14 Photographs showing the blocked choke station piping and clearing those pipes

5 Moving forward

The 620L choke station was installed as a bridge to allow improved UDS performance, while a project to upgrade DBS's backfill system was completed. Its installation was to overcome the limitations of the UDS due to the shape of the pipeline profile. It was done by keeping the upper portion of the UDS in full flow and reducing the slack flow in those areas.

There have also been some operational issues which have limited the use of the chokes station.

The choke station has performed as expected, and there is a reasonably good match between the theoretical pressure change calculations and the measured pressure changes. Its installation and use have shown that it is possible to choke a laminar flow CPB system.

Acknowledgements

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