A Review of Pastefill Borehole Design Alternatives

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Abstract
The success of a paste underground distribution system (UDS) is dependent on the proper installation, operation and maintenance of its boreholes. The boreholes that are required over the life of mine, in particular surface boreholes, represent both the greatest cost and risk to the UDS.

The hydraulic and operational aspects of paste boreholes have been presented in multiple publications. However, the design, installation and maintenance aspects are not widely discussed. The decision to proceed with a certain borehole design is typically based on the local project team's knowledge, or the local equipment available to drill and install the borehole infrastructure. Often time, a particular borehole design is selected without a complete understanding of the later operational and maintenance challenges that will arise from the design decisions.

This paper will cover the major design aspects of paste boreholes. Installation and maintenance aspects will be covered in another paper. The purpose of this paper is to present both advantages and disadvantages of the various design options so that the reader may make informed decisions before implementing a particular solution for their paste project.

Key words: borehole piping, suspended, grouted, drilling, liner, ceramic

Introduction
Boreholes, in particular surface to underground boreholes, typically incur significant installation cost and are considered critical infrastructure. If a borehole is non-operational for any reason, the paste system often cannot operate, potentially delaying mining sequences. As such, it is essential for operations to design their boreholes carefully based on their operational needs and geological conditions. Design aspects to be considered include borehole length and angle, installation method, support method, piping and liner types and maintenance requirements. All of these must be evaluated on a case-by-case basis.

This paper explores key design aspects, highlighting the benefits and risks of each. The goal is to provide mining operations, planning to install boreholes as part of their system, with a clear understanding of available alternatives and considerations to make well-informed decisions. Installation and maintenance aspects related to boreholes are not covered in this paper.

Terminology
In the global backfill industry, mining terminology, especially regarding boreholes, varies, often using casing, piping and lining interchangeably, with all three of the items referred to as some form of 'casing' in some regions. For clarity in this paper, specific definitions for these terms are provided and illustrated in Figure 1:

Borehole Casing Typically installed by drillers for hole stability in poor ground conditions. Usually, not specified by backfill engineering, but left to the discretion of the drilling company (as long as its internal diameter (ID) is suitable for future piping etc.). Often only partial depth of hole until good rock is found. (sometimes referred to as 'caisson')

Borehole Piping The main piping (typically steel) installed in the borehole, with a material and pressure rating specification to suit the expected operating conditions, and thickness suitable to manage wear in unlined scenarios (often called a 'string' when installed, sometimes referred to as 'production casing').

Borehole Lining A hard wearing interior coating inside the borehole piping.

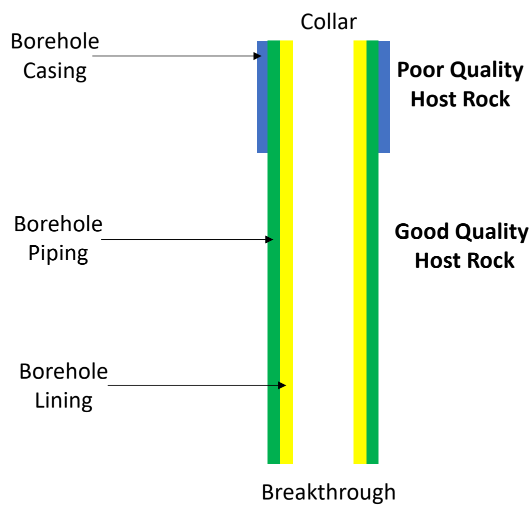

Figure 1. Illustration of borehole terminologies used in this paper.

Disclaimer

The contents of this paper express the authors' industry-based opinions and do not constitute engineering design. Competent individuals should always complete proper engineering design for all aspects of borehole design.

Design Considerations

Borehole Piping

The decision to operate a borehole through bare rock or to insert a pipe largely depends on two factors: the expected operating life and tonnages of the borehole, and the geological conditions in which the borehole is situated.

The decision to install pipe is often simple for boreholes with planned high tonnages or long operating lifespans, except for cases in the most ideal geological conditions. Smaller, shorter lifespan boreholes serving specific stoping areas may be installed in suitable rock without piping, with only pipe inserts installed and grouted in the collar and breakthrough to allow connection to the distribution system. As the expected operating life and tonnage throughput of the borehole increases, the preference leans towards a piped borehole.

Boreholes that require specialized drill rigs to install (typically surface to underground or long bypass underground boreholes) are usually piped to extend their operating life, reducing the frequency at which these rigs must be contracted on site. Boreholes that can be re-installed by on-site production drills or raisebore machines (typically shorter interlevel boreholes) can remain unpiped. In case of failure, these boreholes can be redrilled at minimal cost and operational delay.

Paste boreholes with no piping installed have been proven to operate well in good quality rock masses with few structures. However, where poor quality, reactive, unravelling rock masses with significant structures exist, using pastefill and high-pressure water and air flushing with no piping can quickly lead to borehole failure and blockage of the underground distribution system (UDS). For pumped systems operating > 10 MPa (1450 psi), piping in boreholes becomes more critical as the increased operating pressures can fracture the exposed rock mass, similar to hydraulic fracturing techniques used in oil and gas extraction. Mines with high rock stresses and seismicity should also install piping to mitigate against borehole shearing and fracturing (Figure 2). A geotechnical pilot hole can also be drilled and surveyed prior to reaming, to quantify the borehole's stability prospects. In general, it is typically best practice to assume that surface boreholes will need to be piped.

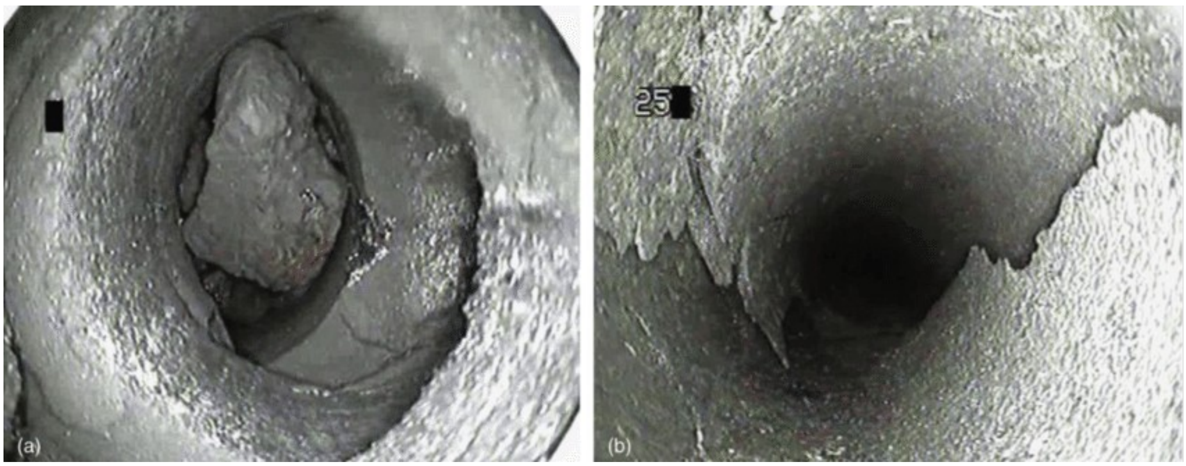

Figure 2. Sheared and fractured boreholes in high stress rock masses (Zhang 2017).

The water in or outflow from the borehole, relating to the hydrogeology of the borehole location also heavily influences the need for borehole piping. Controlled water content in pastefill is crucial to achieve specific strength and rheological characteristics. Any water lost or gained from exposure to the bare rock will alter the pastefill material. The most common case is a borehole adding water to the paste. An example for this case is shown in Figure 3 for a mine in South America with unpiped boreholes. In this example, the paste mass concentration dropped considerably by the time the paste had reached the stope. For an 80 m^3/h (350 usg/m) paste system, borehole water ingress from the surrounding rock of 2 m^3/h (9 usg/m) reduced the paste mass concentration by a full percent. This reduced the paste yield stress by over 200 Pa and 28 days strength by > 10%. Also, this reduction is not apparent in QA/QC samples taken at the paste plant, misleadingly suggesting good pastefill quality as these samples are taken prior to water ingress.

Figure 3. Unpiped borehole with significant water ingress flowing through piping.

It is not recommended to use plastic piping such as High Density Polyethylene (HDPE) as borehole piping. HDPE is not suitable for high pressure operation, weakens in hot conditions, wears out easily in high impact scenarios and is susceptible to vacuum collapse. During failure, the HDPE pipe can collapse (Figure 4). In this example, the HDPE piping in the borehole failed due to insufficient mechanical fastening, then proceeded to fold up and pass through the steel piping at the breakthrough. If using HDPE, plastic welding is recommended to join pipe lengths, rather than mechanical methods to ensure piping continuity within the borehole.

Figure 4. Failed HDPE borehole piping protruding out of level piping leading to a line blockage.

Borehole Angle

Inclined boreholes with a dip of approximately 70° offer several advantages. These include reduced dynamic forces during start-up, reduced incidence of air entrapment or compression within the pastefill, more controlled borehole wear and reduced breakthrough pipe elbow wear. Computational Fluid Dynamics (CFD) modelling results (Figure 5) presents the behaviour of pastefill on startup in both an angled, and vertical borehole. The angled boreholes promote smoother paste flow along the pipeline invert, minimizing air entrapment and allowing for good prediction and control of pipeline wear. In contrast, vertical boreholes show a chaotic leading edge of paste, increasing the risk of air entrapment and unpredictable wear of the pipeline or lining.

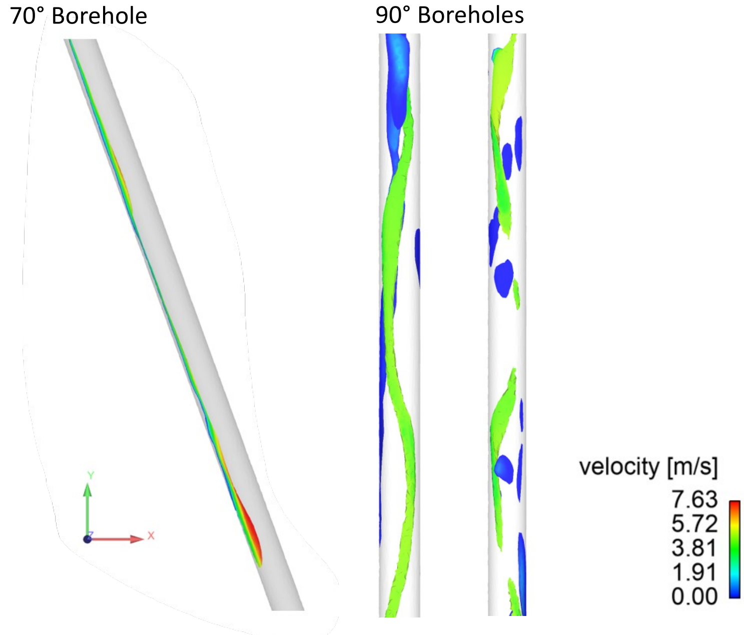

Figure 5. CFD modelling of paste start up flow in an angled and vertical borehole.

As mines develop deeper, there is a growing demand for single-lift boreholes from surface > 1000 m. Using schedule 120, NPS 8 (DN 200 or 200 mm) borehole pipe (typical of a 150 m^3/h system), requires angled boreholes with a diameter exceeding 12 in diameter for the entire borehole length for ease of pipe installation. This exceeds the capabilities of many readily available drill rigs, even in established brownfield areas. Opting for vertical boreholes allows more drill rigs to be considered. In areas of poor ground conditions, drilling long angled boreholes can be impossible, even with suitable drill rig availability. Consequently, operations that require long surface boreholes favour vertical options to save on installation cost and complexity. However, understanding the risks associated with long vertical boreholes is crucial.

Choosing between permanently installing the borehole pipe through grouting or opting for a removable (suspended) installation impacts design decisions, as discussed later in this paper. An available drill rig may be suitable to lower the borehole pipe string down a vertical or angled borehole. However if retrieval is required, the rig may not have sufficient hydraulic pullback capacity to lift the self weight of the string whilst overcoming friction of the string on the borehole invert of an angled hole. If a suspended borehole is preferred, a vertical borehole may be necessary. In some cases, especially in very shallow angled boreholes, the drill rig is required to push the piping into the borehole as the friction is greater than the pipe's weight.

The rock mass quality also affects the drilling process when aiming for a drive-sized target over an extended borehole length. Geological features such as faults and dykes can further complicate achieving a relatively straight borehole. This can be partially negated by using navigational drilling but at an additional cost. Installing the borehole piping blind (no ability to inspect the breakthrough) and developing out to it helps mitigate drilling inaccuracies within reasonable distances. The shape of the borehole (ie, a 'corkscrew' or 'kink') also impacts the ease of pipeline installation. This is less important for a permanently installed borehole pipe compared to for suspended borehole pipe, as installation is only required once.

Borehole Pipe Fastening

Overview

The choice between a permanent or removable borehole pipe depends on many variables including but not limited to system design life, borehole depth, pipe selection, ease and cost of drilling, desired and available maintenance programs, and the risk appetite for the end user.

The authors experience has shown that in Australia and in Southwest USA, most boreholes are suspended systems. Other parts of the world tend to grout the piping to reduce the risk associated with failure under tension.

Permanently Installed Piping

Modern high-performance piping and liner materials (discussed later in this paper), could allow for sufficient longevity over the mine's lifespan with a single or multiple boreholes grouted in place. In situations where the expected tonnages are low and borehole operating lifespan is short, grouting in place is often preferred. This allows for improved installation methods, reduces the risks of pipes failing under tension because of abrasive wear, reduces wear monitoring requirements, eliminates external supports and the risk of a suspended load, and allows the borehole to be used until wear is seen through to the grouted annulus.

For short and easily drilled boreholes, especially when using readily available, site owned operational surface or underground rigs with 6–10-inch reaming bits, installing a new borehole is relatively cost-effective. In these scenarios, the benefits of a grouted borehole pipe largely outweigh the cost and complexity of a suspended system.

For very long boreholes, grouting the borehole piping allows for the well proven float-in installation method. This minimizes the required drill rig size. A typical float-in installation involves sealing the bottom of the borehole, or drilling a non breakthrough hole, flooding the drilled hole and fitting a float shoe to the first pipe. The sealed borehole pipe string is lowered into the flooded hole and floated into position, providing a dramatic reduction in relative mass required to be supported by the drill rig. Once the string is completely assembled and located in its operational position, grout can be pumped down the inside of the piping through the shoe and back up the annulus displacing the water. The grout is then allowed to set sufficiently to support the string itself.

Grouting of boreholes is a proven and straightforward process used globally for backfill operations. Where limited access to borehole surveying is available, a grouted borehole may be the lowest risk option.

Removable/Rotatable Piping

As mine lifespans are extending, driven by increased ore and paste production targets, the need for borehole piping change-outs or drilling replacement holes becomes more likely, even with the best ceramic material lining. In recent years, there has been a growing preference for engineered (supported) suspended systems due to their economic advantages. These systems allow for replacement of piping, (or even sections of the piping) without re-drilling of the borehole itself. Additionally, a suspended system offers the flexibility of being rotatable to distribute the wear around the circumference of the pipe inside diameter (ID). This can be performed mechanically with a drill rig (or crane), or alternatively a rotatable wellhead can be fitted which allows the pipe string to be rotated at will with a simple hydraulic pump. This suspended option, however, has several risks to be considered including installation challenges, change-out downtime, support design, coupling design and wear monitoring to ensure tensile strength is maintained, all of which are discussed below.

Regarding initial or re-installation of the piping, the float-in method discussed earlier, effective for grouted systems, may pose challenges and higher risk for a suspended system, though not impossible. A plan is necessary to transfer weight from buoyancy of the flooded borehole to the structural supports either at the collar, breakthrough or both.

Replacing borehole piping once worn may also involve significant operational downtime and specialised equipment, which can be costly and delay mine sequences if a standby borehole is not available. However, a mine in NSW, Australia successfully replaces their suspended 830 m vertical surface borehole piping in a 5 day period using an Epiroc RD20 surface drill (Figure 6). The site uses 765m of 12 m long 5 in steel pipes for the upper portion of the borehole, and 65 m of IMATECH Armorpipe 9200 ceramic lined pipe for the lower portion and breakthrough piping. The smaller outer diameter (OD) of these pipes compared to conventional 6 and 8 in steel paste pipes, makes the use of the RD20 drill rig practical, as this drills mast height is required to manage the 12 m long lengths. While this case demonstrates a good example of successful replacement of a suspended borehole pipe with minimal operational downtime, it is unique due to its use of smaller diameter and long individual section length piping, which may not be practical for all operations.

Figure 6. Epiroc RD20 drill rig swapping out mines' surface borehole pipe.

As discussed earlier, the borehole depth and available rig pullback capacity may also eliminate the option to retrieve the piping, and as such a suspended design would not be a suitable option. In the event of a borehole blockage, the self weight of the pipe, the full column of cured paste, and friction between the pipe and casing or bare rock, amongst other forces, must be considered in the retrieval process. Furthermore, if the pipe blockage recovery plan is to drill out the blockage rather than replace the piping, the feed pressure of the drill (either drilling down or up from either end) must be considered in the borehole piping support design, along with the pipe and paste weight.

The tensile strength of the piping and joints are also an important factor in identifying if a system may be suspended. Particularly with unlined (steel) piping, the wear allowance is often dictated by the piping thread design. Mechanically, the thread should be selected with enough tensile capacity to support the entire string, when full of paste, with the required wear allowance added. Welding the borehole pipe string is also an option to improve overall tensile capacity, though it can be difficult with some hardened steel materials and ceramic linings. This is discussed later. As an example, in a Copper mine recently surveyed, NPS 8 (DN 200 or 200 mm) schedule 120 (API 5L X42) piping is used for suspended interlevel boreholes. Although the 18.2 mm pipe wall thickness seems robust, the thread design requires a 12.6 mm wall to guarantee the tensile strength and safety factor of the joint, leaving a 5.6 mm wear allowance. Where only a small wear allowance is used, there is an increased risk of the joint failure should a lateral wear groove develop through the length of the pin (male) part of the joint as it could collapse internally, allowing the pipe to part under tension. Therefore, a lower wear allowance must be considered in suspended systems.

When designing a ceramic lined system, the joint is designed to provide the mechanical properties without any lining, therefore the full thickness of the ceramic (typically 8–20 mm) is the wear allowance. Should steel be exposed, then it is assumed the wear allowance has been exceeded and the piping would be changed or rotated to an orientation where areas of concern are at 9 to 3 o'clock. The authors estimate that regular rotation of a suspended inclined borehole may increase the life by > 300% depending on the nature of the wear. Vertical boreholes also benefit from this due to small borehole piping deviations, though to a lesser extent.

The maintenance schedule is also one of the most critical aspects of operating suspended systems. A borehole breach, even without tensile failure, can quickly turn a suspended system into a semi-grouted system, making retrieval difficult or impossible. To address this, from a maintenance perspective, it is advisable to proactively conduct regular borehole surveys early in the system's life to identify wear rates. These wear rates then dictate when future inspections should occur so that areas of high wear can be addressed before a breach occurs. Other methods of managing this include annulus flushing after each pour to identify and remove paste that has entered the annulus thus identifying a breach. The flushing water can be monitored with CCTV systems.

Hybrid Options

There exists a hybrid option where a larger ID pipe may be installed and grouted in place, initially. O nce its wear life is reached, a smaller pipe can be lowered down inside and either suspended or grouted in place, extending the operating life of the borehole without redrilling or removal of worn piping. Due to the pipe wall thickness, and annulus clearance required for installation, potentially very low and very high paste velocities may be seen in the first and second borehole pipes, respectively. This will affect the full system hydraulics due to varying friction losses and must be confirmed as suitable during the design stage.

Supporting The String

For suspended applications, the string can be designed with a wellhead, either fixed or rotatable, which can support the string under tension when in full plug flow operation. Figure 7 shows an example of a rotating wellhead, allowing borehole pipe rotation without drill rigs or other external mechanical equipment. Bottom supports may serve as backup in some cases, should the piping fail under tension. Depending on the borehole length, the bottom support may be designed with enough clearance for thermal movement, but close enough to catch the string if required. The support should also be designed so that the high wear components such as elbows can be changed as required.

Figure 7. A hand operated rotating wellhead fitted to a 150 m NPS 8 borehole pipe.

Both collar and breakthrough supports can be used, with bottom only supports shown in Figure 8 being engineered and installed successfully for an operation in Southwest USA. A top guide support was included for lateral support and to catch the string in case of a failure. It is not recommended to engineer a fixed support for both collar and breakthrough, as thermal expansion and contraction of the pipeline may lead to buckling or tensile failure of the pipeline within the borehole. One end must have some flexibility in the borehole centerline axis.

There have been reports of buckling of a borehole pipe within the borehole where only a lower support was installed, leading to a high wear area and frequent pipeline failures in the area. This problem was resolved by adding tension to an upper support, but thermal expansions needed consideration. A hydraulic or spring system may be implemented on the upper support to provide tension, while also allowing for movement along the borehole centerline axis.

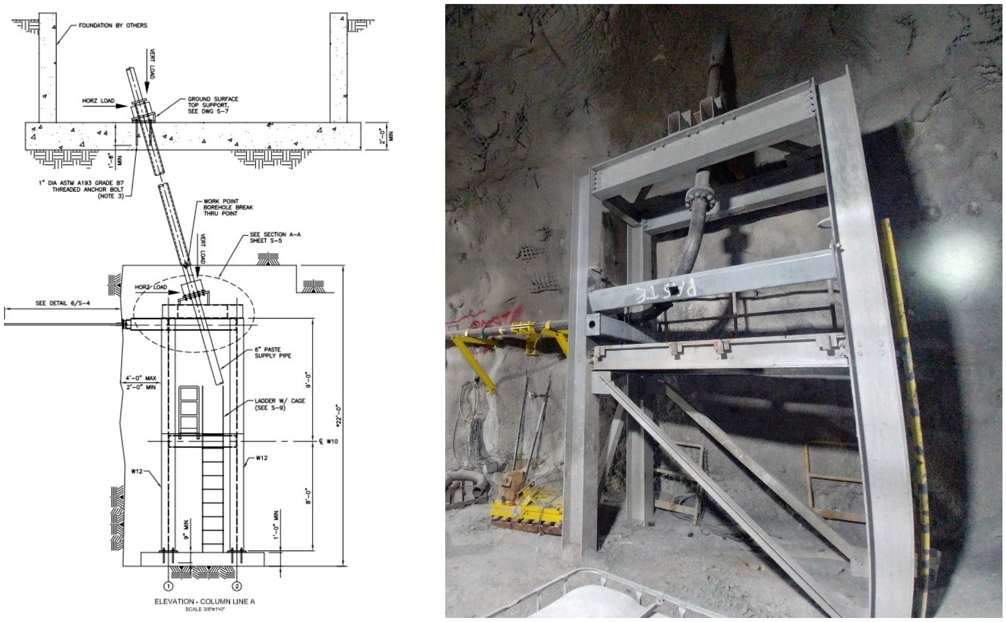

Figure 8: Example of top and bottom borehole supports and the constructed bottom support for a suspended borehole pipe.

Failure of a Suspended Line

When preventative maintenance fails to prevent a tension-induced piping failing and the string is still supported at mine level, a drill rig can often retrieve the string after a suitable risk assessment. After any top suspended pipes are removed, pipes that have failed but remain in the string can often be 'fished' out with tools common to the drilling industry.

If the system has resulted in a breach and the pipes become inadvertently grouted in place, there are several methods of removal that can be attempted. In some cases, a drill rig can work the pipes free, if not a crane supported vibrator can sometimes be used to free up the pipes and remove them. The thread design does play a role in this, in that a flush joint (a thread where the external is smooth) is easier to 'free up' than a coupled pipes with external shoulders; the coupled connection will typically have a much greater tensile strength, therefore more force can be applied. Before attempting this, the pipe vendor should be consulted to identify the rated tensile capacity of the thread.

Joint Design – Welded or Threaded Connections

Overview

Typically, couplings, flanges, welding or threaded connections are used to connect paste piping. Couplings and flanges, requiring significant 'headroom' around the pipeline itself, are not suitable for borehole connections. As such, welded or threaded connections are typically used in borehole scenarios.

Welded Connections

Welded piping connections lead to the lowest-cost piping, as the ends of each pipe are simply bevelled for later welding, eliminating the need for precise machining of grooves or threads. However, their installation requires more time, labour, and quality control due to alignment, welding and inspection of each joint.

The weld is typically specified to equal or exceed the tensile strength of the piping. Provided the piping is specified correctly and welding completed to standards, the joint's pressure rating and tensile strength are adequately managed.

Welded connections are a suitable method of borehole piping connection, where precise thread engineering or machining is unavailable, or a low-cost permanent installation is desired. However, if removal of the pipeline is anticipated, threading is preferred for easier removal, avoiding the need for destructive cutting. In all scenarios where specialised steel or internal linings are to be used, welding is also not recommended and may not be possible.

Threaded Connections

When threading steel piping, industry-standard buttress threads, or O&G (oil and gas) 'casing' are commonly used. While termed 'casing' in the oil and gas industry, it's referred to as piping in a backfill context due to the role it plays. However, this piping isn't always ideal for backfill, which is a slurry transportation application. When selecting a commercially available "Premium" thread, consider factors like the internal profile, the required joint strength, pressure rating and the required makeup torque.

Ideally the joint's internal profile should be flush, with minimal gap between the pipes. As mentioned earlier, the thread should be designed to provide the required joint strength without considering the additional wall thickness that provides the wear allowance. Most traditional buttress threads do not have an internal shoulder, rather the final make-up position which dictates the final joint gap is a function of torque and machining tolerances. The results can be a string where the 'nose gap' varies from joint to joint. An excessive gap can result in turbulence and excessive wear, as such a gap of less than 0.5 mm should be targeted.

The pressure rating of a thread depends on surface area, friction, and torque. Threads are often relatively fine with high makeup torque used to achieve this pressure rating making them challenging to assemble without cross threading and may be difficult to break out when required. As the materials used for steel backfill piping are often mild steel (eg, Grade B, X42, X52), galling can be expected on breakout which also may limit reuse.

In a suspended system, for reusable borehole piping with the option of easy replacement, coarse threads with integrated seal designed specifically for paste fill are available and excel over finer threads. They are more robust, less prone to cross-threading, require less toque and feature a positive internal shoulder to minimize joint gaps. These joints allow for multiple reliable uses and are designed with a true smooth bore, making them the go-to choice for pastefill applications. Figure 9 illustrates examples of a fine and coarse thread for comparison.

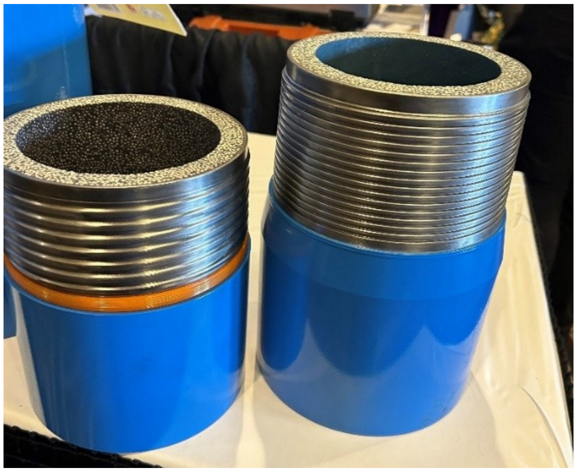

Figure 9: Pipe threading examples with a low torque integrated seal thread (left) and fine thread (right).

The choice between a flush joint and a coupled thread depends on the tensile load requirements and installation method. For drill rig installation, a flush joint is ideal, while a coupled connection can simplify the installation when using a hydraulic tong and crane. Couple threads also provide higher tensile capacity when needed.

Borehole Pipe Types and Liners

To improve wear properties, and sometimes pressure ratings, there are variations of borehole pipe types and internal linings readily available for backfill applications.

The type of pipe used for a UDS depends on operating factors (eg, pipelines operating in full flow will experience less wear than pipelines in partial/slack flow) and the backfill composition (eg, a backfill with harder minerals will experience more wear than one with softer minerals). A pipeline material's wear rate is a primary concern, but overall pressure rating performance and impact resistance also matter depending on the application. The self weight of the pipe type and liner also play a part in the installation design considerations.

Borehole steel pipes vary from mild carbon steel to high strength carbon steel to differentially hardened steel. Their benefits are as follows:

- Mild carbon steel is the most commonly used type of pipe for backfill applications. It is the cheapest and most readily available of the potential options. However, it tends to experience the highest wear rates. This can be mitigated by the lower cost of replacement (depending on the type of borehole installation). Opting for mild steel pipe with larger wall thicknesses can provide a longer operating life for relatively low-cost increases. However, it is important to ensure that the pipeline's IDs are relatively matched. This type of pipe is usually welded but can be threaded.
- High strength steel pipe has a higher allowable stress and toughness than mild steel, resulting in improved wear and pressure-related performance compared to a mild carbon steel pipe of similar dimensions and operating envelope. This piping is typically more expensive and may be less available than mild steel options. The most common example of this type of pipe is 'drill casing' and is also be referred to as 'oil and gas casing' or pipe. This type of pipe can be welded but is typically threaded.
- Differentially hardened steel pipe, achieved through methods like induction, nitride, etc, enhance the inner surface hardness providing superior wear resistance compared to mild carbon steel pipe of similar dimensions and operating envelope. This option is the most expensive option of the three pipe types. This type of pipe is almost always threaded or flanged.

Lined borehole pipe generally consists of an outer steel skin supporting an inner material. To maintain the pipeline's internal diameter, a thinner walled steel pipe is typically used. Note that the use of thinner walled pipe can affect the pipeline's pressure rating, and tensile strength once threaded. Key design considerations for lined pipes include:

- Lined pipes can be significantly more expensive than unlined steel pipes and, therefore, need to provide a significantly longer operating life to be cost effective. There are various types of liner materials ranging from basalt, mortar, epoxy, ceramic plates, carbides, rubber, ceramic bead impregnated epoxy resin, etc. However, specific liners are more suitable for backfill operations (eg, rubber liners cannot operate in vacuum, brittle liners, like basalt, mortar, and ceramic plates, have poor impact performance, epoxy does lack sufficient wear resistance). Ceramic bead impregnated epoxy resin liners are the typical liner used in backfill boreholes due to their improved wear performance and ability to withstand the impacts associated with freefall. Carbides, such as chromium, are also starting to be used in backfill systems. Other types of liners are not used unless there is a specific reason to do so.

- Most lined pipes are threaded or flanged only, which requires specific installation methods (drill rigs, hydraulic tongs, etc.). Some of the carbide liners can be welded, but require specialized techniques and equipment poorly suited to field use.
- Given the cost of lined pipe, it should only be used in areas where extra wear performance is required. This may further benefit a project when the pipe is removable, extending the time between change outs. Compatibility between the threads of the lined and unlined steel pipes must however be considered.
- When attempting to drill out a blocked lined pipe, greater care must be taken to avoid damaging the liner. Any damage can accelerate wear by creating turbulence in the borehole piping. The authors have noted successful instances of unblocking ceramic lined pipes at various sites.

An example of the life extension from unlined steel to ceramic lined steel is that of a copper mine in North Queensland Australia. This was a vertical borehole where the unlined piping was suspended in the top 150 m of a 750 m, 4.5 in ID borehole. The lower 600 m was unpiped in solid country rock.

Various lining materials were trialled, including hard but brittle monolithic materials such as basalt. However, inconsistent performance and premature delamination issues arose, sometimes prior to 100,000 t of fill. This lead to blockages and ruptures, causing grouting of the piping within the borehole and resulting in high replacement costs, and in some cases, loss of the borehole.

The system temporarily reverted to steel piping (using P110 oil field ‘casing’ pipe), although the life was limited to 150,000 t of fill. Eventually, an ArmorPIPE composite ceramic lining was adopted extending the system to ~ 6,000,000 t of fill. This change resulted in savings due to reduced pipe purchases, reduction in loss of boreholes and elimination of costly change-outs. Figure 10 shows a visual comparison between the original oil field ‘casing’ piping and the upgraded ArmorPIPE ceramic lined piping used in this application.

Figure 10. P110 Oil Field ‘casing’ pipe shown completely worn through after 150,000 t of fill (left). ArmorPIPE inspection in same application after 2,000,000 t of fill (right).

Summary

In summary, where shorter lifespans, excellent rock conditions and little water inflow exists, unpiped boreholes are a possibility, however in all other applications, and as is typically recommended, piping should be installed to reduce risks of borehole failure.

The dip angle of the borehole is recommended to be approximately 70° to improve start up flow conditions, however in many suspended or very long borehole scenarios, vertical boreholes may be required to allow for ease of installation, rotation, and removal.

Grouted borehole pipes are the recommended starting point for a paste borehole design, simplifying installation, maintenance, and support of the borehole. However, where rotation, and replacement are desired to extend the borehole operating life without costly re-drilling, a suspended system can be implemented. If suspended, the supports and pipe joints must be engineered such that pipe weight, paste weight, and dynamic forces are managed. Pipeline surveying, maintenance, removal and replacement must also be considered in the design.

Lastly the choice of steel type and hard-wearing liner is typically an economic decision based on the predicted lifespan and operation conditions of the borehole. Although these options can extend the operating life of the borehole pipe, they come at a considerable cost.

With these design considerations in mind, sites planning to install pastefill boreholes can better direct their engineering resources to efficiently develop the most suitable design for their application. It is important that the specifics of the particular site and borehole are considered in the borehole design process, rather than following what has been done before at the site or in the local region. As each mine, paste system and borehole setting is unique, what is considered most suitable for one borehole will likely not be the case for others nearby.

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Acronyms

DN	Diameter Nominal
HDPE	High Density Polyethylene
ID	Internal Diameter
NPS	Nominal Pipe Size
OD	Outside Diameter
UDS	Underground Distribution System