Design procedure for hydraulic backfill distribution systems

by R. Cooke*

Synopsis

A wide range of materials are used in hydraulic backfilling operations and the pipeline flow behaviour of these mixtures varies considerably. It is shown that despite the large differences in constituent materials and flow behaviour, a common approach can be applied to analysing the flow of all hydraulic backfills. This is extended to include a rational design approach for backfill distribution systems. The use and limitations of pipe loop tests as a design aid is discussed. Backfill quality control is identified as a key area where improvement needs to be made to enhance the reliability of backfill system operation.

Introduction

Hydraulic backfilling has become an integral part of many mining operations. Backfill can comprise combinations of diverse materials such as total tailings, classified tailings, crushed waste rock, gravel and sand. Binders and chemical additives may be added to improve mechanical, placement and transportation properties. It is common practice to classify hydraulic backfills into two groups based on their *in situ* dewatering characteristics. Slurry backfills typically have a solids concentration of less than 70% by mass and require dewatering facilities in the stopes. Paste fills typically have solids concentration greater than 70% by mass, contain binders and little or no water drains from the backfill after placement.

This paper presents a rational design approach for backfill distribution systems by considering the backfill flow behaviour, pipe loop testing, distribution system type and backfill quality control.

Hydraulic backfill flow behaviour

Before considering the design of a distribution system, it is important to have a thorough understanding of the backfill flow behaviour. It is useful to divide the solid particles into two fractions when analysing the flow behaviour of any solid-liquid mixture:

- The fine particles, generally considered to be particles smaller than 75 μm, mix with the conveying liquid (usually water) to form the vehicle. The vehicle rheology, which may be Newtonian or non-Newtonian, is a function of the fines concentration and the physical and chemical properties of the fines and conveying liquid
- The coarse particles (+75 μm) are suspended in the vehicle by one or more of the following mechanisms: turbulence, interparticle contact and the vehicle yield stress.

Hydraulic backfills are usually classified as slurry or paste fills. However, as a starting point, it is more useful to examine the flow behaviour of the constituent materials. Total and classified tailings are most widely used for hydraulic backfills and the flow behaviour of these mixtures is discussed below. Figure 1 compares the size distributions of typical total and classified tailings.

Classified tailings

Classified tailings backfill is usually produced by removing the fine fraction of total tailings using hydro-cyclones. This is done to improve the drainage characteristics of the fill (typically 100 mm per hour is required). Generally the backfill is transported and placed at the concentration produced by the cyclones (35 to 45% by volume)—i.e. no additional dewatering is required.

For most classified tailings, the vehicle has a Newtonian rheology due to the low concentration of fine particles. Visual observation through a clear pipe is the best way of understanding the flow behaviour of any solid-liquid mixture. Figure 2 shows a plot of typical classified tailings flow behaviour observed for a range of solids concentrations and flow velocities. Two flow regimes related

---

* *Paterson & Cooke, Consulting Engineers (Pty) Ltd, Cape Town, South Africa.*

© *The South African Institute of Mining and Metallurgy, 2001. SA ISSN 0038–223X/3.00 + 0.00. Paper received Oct. 1999; revised paper received Oct. 2000.*

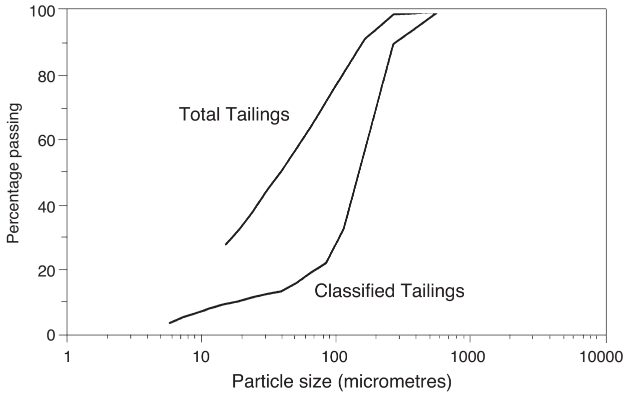

Figure 1—Typical tailings size distributions

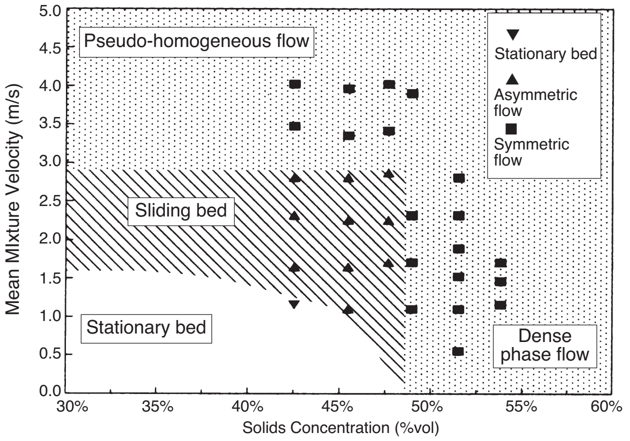

Figure 2—Observed classified tailings flow behaviour

to the freely settled solids concentration (C_{free}[1]) are observed (Cooke[1991]):

- For concentrations less than C_{free}, a mixed regime slurry is formed. The coarse particles are suspended by turbulence and interparticle contact in the vehicle. In a horizontal pipe, the flow regime is characterized by an increase in particle concentration towards the pipe invert. At high flow velocities, the mixture appears homogeneous (termed pseudo-homogeneous) owing to the uniform suspension of solid particles by turbulence. As the mixture velocity is decreased, particles settle, initially forming a sliding bed and then a stationary bed. The sliding bed is noted for the 'pulse-like' movements associated with the formation of dunes in the pipeline (in some installations, the sound of the dunes moving through the pipeline can be clearly heard). The friction losses are greater in horizontal pipes than vertical pipes with the difference decreasing with increasing solids concentration and mixture velocity
- For concentrations greater than C_{free}, a dense phase mixture is formed. The dominant mechanism supporting particles is interparticle contact—the mixture is essentially a settling mixture in which the solids particles are prevented from settling by the high concentration of solid particles. There is little difference in the friction losses for horizontal and vertical pipes.

Figure 3 shows typical pressure gradient versus flow velocity relationships for high and low concentration classified tailings. Figure 4 illustrates how rapidly the pressure gradient increases with solids concentration for concentrations greater than C_{free}.

The addition of cementitious binder has little effect on classified tailings flow behaviour for the range of solids concentrations normally used in backfill distribution systems (Cooke *et al.*[1992]).

Classified tailings backfill slurries generally have solids concentrations close to or less than C_{free} and are referred to as **slurry backfills**. The main disadvantage of slurry fills is the amount of water that drains from the stopes and must be pumped back to surface. Currently classified tailings systems are not operated at concentrations significantly greater than C_{free} (i.e. a dense phase backfill). This is mainly due to the sensitivity of the pressure gradients to small concentration changes and the consequent potential for pipeline blockages.

The above discussion also applies to any hydraulic backfill with a small percentage of fines (e.g. waste sand or rock).

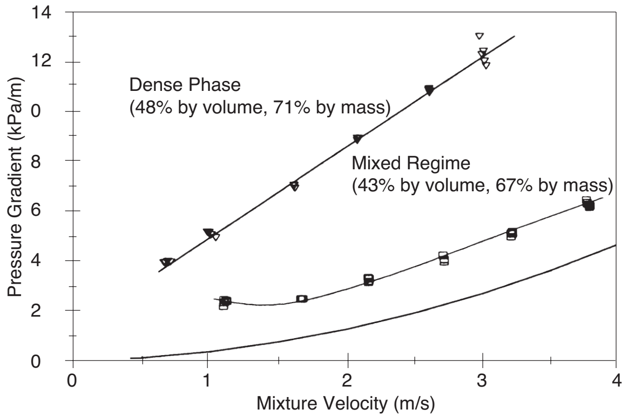

Figure 3—Classified tailings (40 mm pipeline)

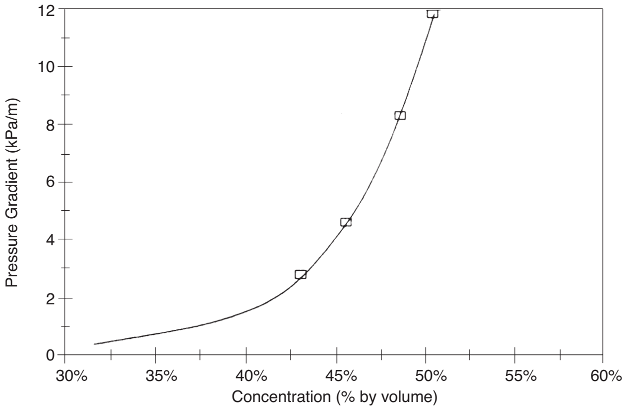

Figure 4—Classified tailings—pressure gradient versus concentration (40 mm pipe, 2 m/s)

---

[1] **The freely settled concentration is determined by allowing particles to settle through water and assume their freely settled (or loose poured) packing. C_{free} is defined as the ratio of the volume of particles to the volume occupied by the particles.**

Total tailings

Conventionally, total tailings backfills are dewatered by sedimentation in thickeners. If required, additional dewatering is performed by vacuum filtration followed by mechanical mixing to break down the filter cake structure. A range of new dewatering technologies being developed include high rate thickeners and fluidization (Hassani and Archibald[1998]).

For total tailings backfills, the vehicle rheology is non-Newtonian due to the relatively high concentration of fine particles. Figure 5 shows typical pressure gradient versus flow relationships for total tailings. Two distinct flow regimes are noted—laminar and turbulent flow. In laminar flow the vehicle rheology dominates the friction losses and the coarse particles are maintained in suspension by the vehicle yield stress. The mixture density dominates the friction losses in turbulent flow with turbulence maintaining the coarse particles in suspension. The yield stress, apparent viscosity and transition velocity from laminar to turbulent flow increase with increasing concentration. The particles are uniformly distributed across the pipe section and the vertical and horizontal pipeline friction losses are equal.

For solids concentrations less than C_{free}, total tailings mixtures are considered to be **slurry backfills**. At solids concentrations greater than C_{free}, total tailings mixtures are considered to be **paste fills** and there is very little or no water run-off after placement in the stopes. Cementitious binders are added to most total tailings backfills to reduce water run-off, provide strength and avoid liquefaction.

The addition of binders affects the rheology of the mixture by increasing the yield stress, apparent viscosity, and transition velocity between laminar and turbulent flow as shown in Figure 6 (Cooke and Spearing[1993]). At high solids concentrations binder addition can produce time-dependent flow behaviour due to hydration of the binder. This can lead to pipeline blockages as shown in Figure 7.

Current practice is to mix the binder and tailings on surface before being transported to the stopes. There are advantages to adding the binder underground immediately before placement in the stopes:

- The addition of binder can double the mixture yield stress. By adding binder at the end of the pipeline, it may be possible to transport backfills at higher solids concentrations
- There is no danger of hydration occurring during pipeline transport with the consequent potential for pipeline blockages
- Verkerk[1984] reports that un-cemented total tailings backfill can be left in the distribution piping for periods of up to 5 days without flushing.

This approach was followed for the Preussag system at Bad Grund Mine where the cement was conveyed to the stopes via a pneumatic pipeline system (Lerche and Renetzeder[1984]). As the capital and operating costs for pneumatic transportation systems are high, consideration should be given to transporting the binder hydraulically by pipeline. Although this requires an additional pipeline system, the bore will be small and significantly reduced amounts of pre-and post-flushing water will be required.

The above discussion for total tailings backfill applies to a wide range of backfill mixes, i.e. blended total tailings and waste rock or sand mixes. The main criterion is that the vehicle yield stress must be great enough to support the largest particle in laminar flow. Landriault *et al.*[1996] note at least 15% by mass of the material must be finer than 20 μm to form a paste fill mixture.

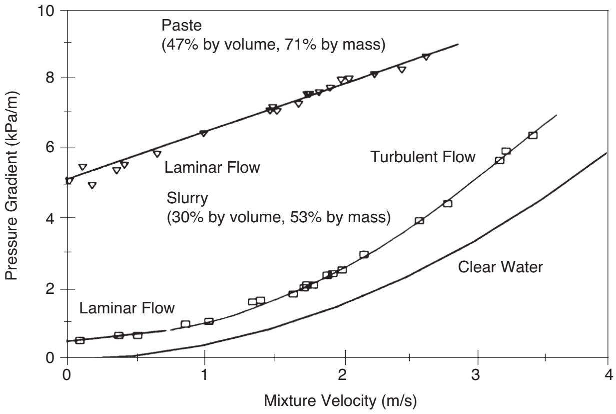

Figure 5—Total Tailings (41.5 mm pipeline)

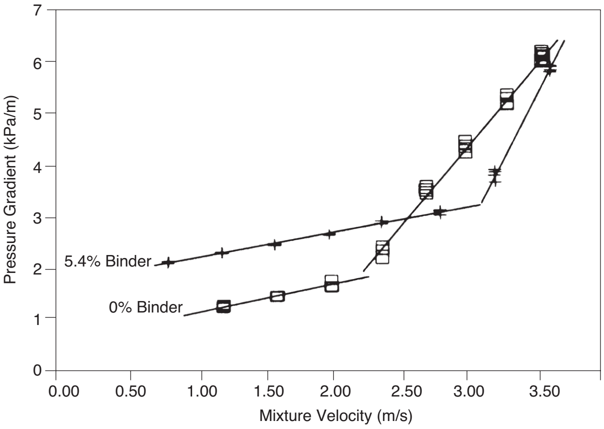

Figure 6—Total tailings-effect of binder addition

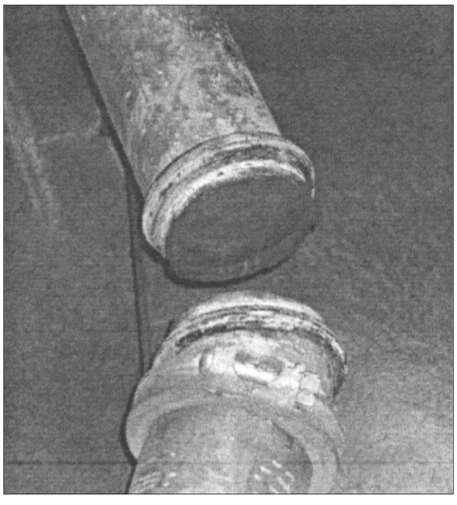

Figure 7—Blocked paste fill pipeline

Pipe loop tests

For some installations it may be necessary to conduct loop tests to establish the backfill flow behaviour prior to designing the system. This is more important for high concentration systems as the variations in flow behaviour increase with increasing solids concentration. The cost of the tests is usually a small fraction of the design savings that can be implemented by having a better understanding of the flow behaviour. Loop tests also help mine operators develop confidence in the backfill flow behaviour. It is beyond the scope of this paper to discuss loop testing in detail, but the following points should be considered before embarking on a test programme:

Clear water test—It important to conduct a clear water test before starting any test work with backfill to verify the proper operation of the instrumentation. The results of the clear water test should correlate with Colebrook-White friction factor formulation. Depending on the condition of the pipes, hydraulic roughnesses of up 200 μm can be expected. Further clear water tests should be conducted during the test programme to check the instrumentation.

Representative sample—Great care must be taken to ensure that the sample tested is representative of the material that will be used for the actual installation. In some cases, it may be advisable to test a range of samples.

Backfill degradation—Any backfill will degrade when re-circulated through a test loop. This does not appear to be a significant problem for total and classified tailings. However, it can be a major problem for coarse waste rock-tailings backfills. For example, the distance between pumps had to be halved due to the higher than expected pressure gradients for a tailings-aggregate system designed on recirculating test loop data. A very small increase in fines content has a significant effect on the backfill flow behaviour which may not be detected through particle size distribution analyses. To avoid nasty commissioning ‘surprises’ it is advisable to conduct once through loop tests for any waste rock backfill blends.

Temperature—It is recommended that recirculating loops are equipped with heat exchangers. It is important to maintain a constant backfill temperature during tests as the backfill rheology varies with temperature. High temperatures also accelerate the hydration reaction for cemented backfills.

Pulsatile flow—Landriault *et al.*[1996] report that the friction loss for paste fill pumped using positive displacement pumps is greater than for gravity flow. Round and El-Sayed[1985] demonstrated that this effect is dependent on the pulsing frequency and in some cases can lead to a reduction in friction losses. Loop tests conducted for gravity flow installations, should simulate the actual flow conditions. This can be achieved by pumping the backfill to a header tank and then allowing the backfill to gravitate from the tank.

Backfill distribution systems

Backfill is transported by pipeline from surface to stopes underground. There are two basic types of backfill distribution systems—free fall and full flow.

Free fall distribution systems

Figure 8 shows an idealized layout of a ‘free fall’ transportation system. Backfill is supplied to the borehole or shaft column pipeline in which it falls freely under gravity until it reaches the air-backfill interface. The height of the interface is established such that the static head available balances the pipeline friction losses in the pressurized section.

The primary advantage of a free fall system is the tolerance to variations in backfill properties and flow rate. The level of the air-backfill interface simply rises or falls to accommodate any change in the backfill flow behaviour or supply flow rate. The disadvantages of free fall systems are:

(i) Sive and Lazarus[1988] report that the backfill terminal velocity in the free-fall zone is estimated to be about 45 m/s. The backfill tends to migrate to the pipe wall resulting in extremely high pipeline wear rates. Any pipe misalignment in the free-fall zone results in severe localized erosion as shown in Figure 9.

(ii) The high impact pressures generated at the air-backfill interface by falling slugs of backfill can lead to pipe ‘bursting’ failure illustrated in Figure 10. This type of failure is more likely to occur for total tailings backfills.

(iii) In case of a pipeline blockage, the air-backfill interface will rise resulting in the normal pipeline operating pressures being exceeded by a significant margin.

(iv) The negative pressures generated due to free fall can lead to air entrainment in the backfill which can cause operational problems at the stopes.

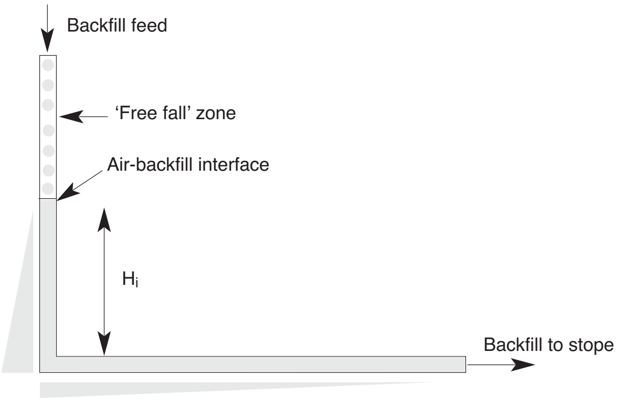

Figure 8—Free fall backfill distribution system

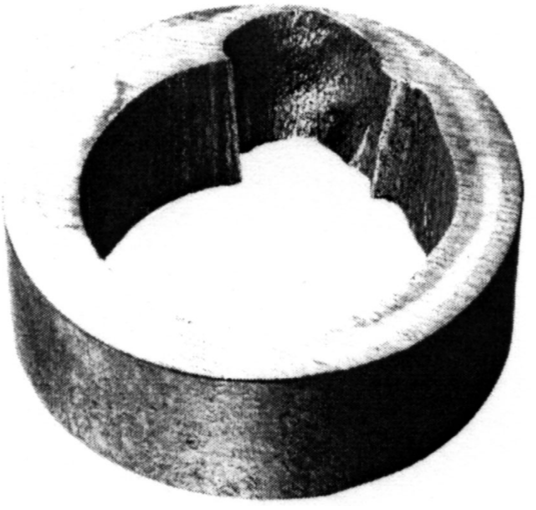

Figure 9—Localized erosion in free fall zone

Figure 10—‘ Bursting’ pipe failure at air-backfill interface

Pipelines are more affected by the items (i) and (ii) above than boreholes. However, boreholes are also subject to wear in the free fall zone and particularly at the air-backfill interface. This can lead to rock spalling and blocking the borehole.

Paterson *et al.*[1998] recommend that pipelines or boreholes are slightly inclined for installations where free fall is unavoidable. This reduces the free fall velocity and wear rates, however, most wear occurs on the downslope side of the pipe or borehole. This is termed a slack flow system.

Full flow distribution systems

Lazarus and Paterson[1988] analysed the source of failures in a South African gold mine free fall backfill distribution system. They suggested that the failures could be overcome by operating the shaft column in full flow conditions. A similar conclusion had been reached by Raj[1974] many years earlier.

A full flow, or balanced transportation system is shown in Figure 11. The air-slurry interface is maintained at surface level by ensuring that the system friction losses match the available gravity head. The advantage of full flow distribution systems is that pipeline wear rates, and hence failures, are minimized. The difficulty in implementing such a system is that typically for low mixture velocities the static head available is far greater than the frictional losses. Sacrificial lengths of small bore choke pipe or energy dissipaters are used to increase the system friction losses.

Design procedure

Figure 12 illustrates the iterative nature of backfill distribution system design. The main design elements follow:

System duty specification

A clear definition of the system requirements and constraints is required before starting the design. This is generally more time consuming than expected.

Backfill flow modelling

It is important that the backfill flow behaviour is accurately modelled for full flow and high concentration systems. The modelling may be based on experience with similar backfills or test work. The test work can range from simple slump cone tests, rheological characterisation to full scale loop testing.

Pipeline wear

Wear is an important factor in the cost of operating a backfill system. Wear is the loss of pipe material due to erosion and corrosion. Erosion decreases with decreasing particle size and increasing solids concentration. Corrosion is an electrochemical process dependent on the chemical properties of the backfill and flushing water. (Bacterial corrosion can also be a problem in some cases.) Postlethwaite *et al.*[1972] note that erosion can significantly increase corrosion rates. Pipeline wear rate predictions are largely based on experience with

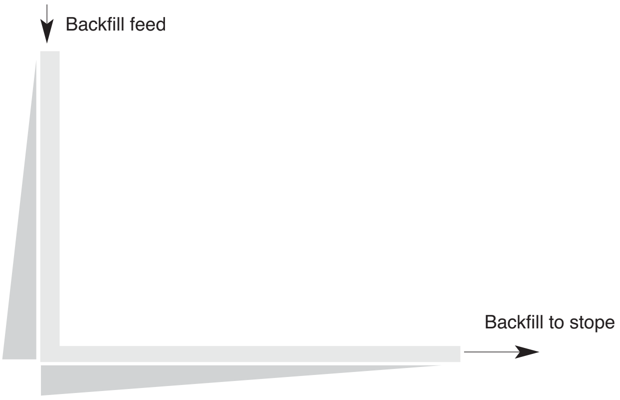

Figure 11—Full flow backfill distribution system

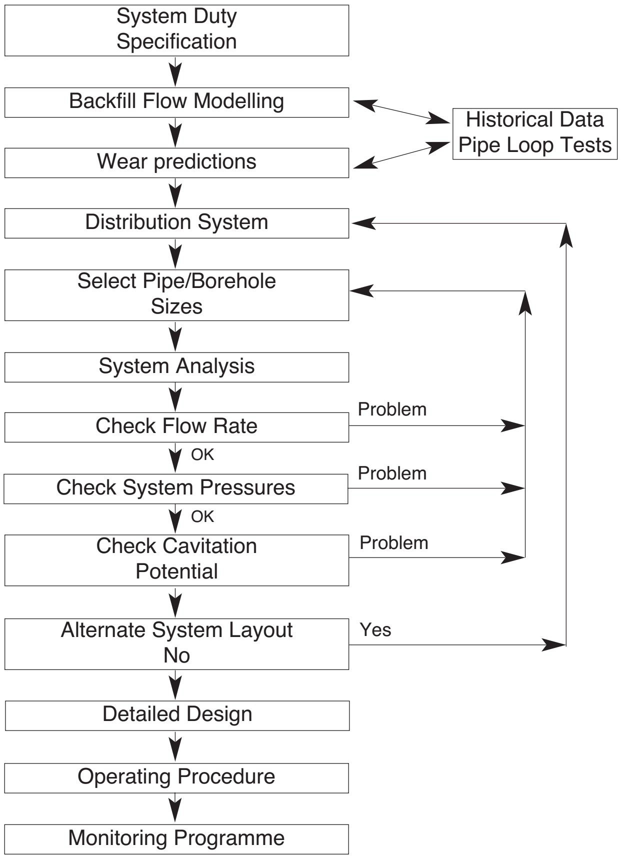

Figure 12—Backfill system design procedure

similar backfills, although loop or bench top tests are also used when required.

It is important to maximize the life of any piping installed in a shaft as it is expensive to replace in terms of shaft down time. Polyurethane lining should be considered for abrasive backfills. High density polyethylene piping should be used where system pressures permit as it is reasonably erosion resistant, does not corrode and can be installed quickly and cheaply.

Distribution system

The distribution system selected is highly dependent on the mine layout. To maximize the system's reliability, pumps and free-fall piping should be avoided.

Piping and borehole sizing

The sizing of backfill distribution system pipes and boreholes is an iterative procedure. In selecting the initial pipe sizes, the following guidelines can be applied:

- The pressure rating of the pipes in the shaft column should be able to withstand the full static head (i.e. pressure at zero flow)
- Based on wear considerations it is preferable to keep the flow velocity below 4 m/s
- To ensure that the flow conditions are stable, the flow velocity should not be below a certain minimum value. In general for classified tailings a minimum value of about 2 m/s can be used while total tailings systems can be operated at about 1m/s. These values depend on the backfill type, solids concentration and pipe diameter and should be confirmed from test work or experience with similar materials
- The pipes selected should be able to provide the required flow rate for the planned pipeline extensions with minimal system changes.

System analysis

For a full flow system, the backfill slurry flow rate must be determined such that the total pipeline friction head loss expressed in metres of slurry equals the total gravity head available, i.e.:

$$H_{\text{available}} = \sum_{e=1}^{n} \Delta H_e L_e + \text{minor losses},$$

where ΔH_e = pipe element friction head loss (metres of slurry per metre of pipe)
L_e = length of pipe element
n = number of pipe elements.

The head loss for each pipe element is calculated using the appropriate slurry flow model. For complex pipeline systems, the balanced flow rate is best obtained using a computer program.

The system behaviour during pre-and post-flushing conditions should be modelled. This is particularly important for full flow systems and slurry backfills.

The interaction of the distribution piping system and the feed from the backfill plant should be examined. Batch feeding is generally undesirable for pipeline transport and continuous feed systems are preferred even if the backfill is produced on a batch basis.

Backfill quality control

The backfill quality must be controlled before entering the piping system to ensure reliable operation. This is particularly important for high concentration systems and represents an area where further development is required.

Current quality control practice for paste fill systems does not provide sufficient information regarding backfill flow behaviour. The slump test is an indication of only one parameter (yield stress) of the three parameters that characterize non-Newtonian mixtures. The backfill plant mixer input power primarily gives an indication of backfill density which is not a suitable control parameter as the flow properties can vary significantly with small changes in solids properties.

Conclusions

A common approach to analysing the flow behaviour of all hydraulic backfills has been presented. Issues relating to loop testing have been discussed and the importance of obtaining a representative sample is noted. It is suggested that there may be advantages to transporting backfill and binder underground separately.

A rational design approach suitable for all types of backfill distribution systems has been presented.

Backfill quality control is identified as an important area for further development.

Acknowledgement

This paper has been presented at the CIM99 Conference held in Calgary in 1999.

References

Cooke, R. The Dense Phase Hydraulic Transport of High Concentration Cyclone Classified Tailings in Pipelines. Ph.D. dissertation, University of Cape Town. 1991.

Cooke, R., Spearing, A.J.S., and Gericke, D. The Influence of Binder Addition on the Hydraulic Transport of Classified-Tailings Backfill. *Journal of the South African Institute of Mining and Metallurgy*, vol. 92, no. 11/12, 1992. pp. 325–329.

Cooke, R. and Spearing, A.J.S. The Influence of Binder Addition on the Hydraulic Transport of Backfill containing Full Gold-Plant Tailings. *Journal of the South African Institute of Mining and Metallurgy*, vol. 93, no. 6, 1993. pp. 143–146.

Hassani, F. and Archibald, J. Mine Backfill 1998, *Canadian Institute of Mining, Metallurgy and Petroleum*. 1998.

Landriault, D., Welch, D., and Morrison, D. Mine Tailings Disposal as a Paste Backfill for Underground Mine Backfill and Surface Waste Deposition. SME Short Course, March. 1996.

Lazarus, J.H. and Paterson, A.J.C. Failure of Vertical Backfill Pipe at Randfontein Gold Mine Cooke III Shaft—Report No. 2, *Hydrotransport Research Report* 88102, University of Cape Town. 1988.

Lerche, R. and Renetzeder, H. The Development of 'Pumped Fill' at Grund Mine - A Successful New Approach to Back-filling using High Density Hydraulic Conveying, *Proceedings 9th International Conference on the Hydraulic Transport of Solids in Pipes*, Rome. 1984.

Paterson, A.J.C., Cooke, R., and Gericke, D. Design of Hydraulic Backfill Distribution Systems—Lessons From Case Studies. *Proceedings Minefill 98*, Australasian Institute of Mining and Metallurgy, Brisbane, April, 1998. pp. 121–127.

Postlethwaite, J., Tinkler, E.B., and Hawrylak, M. Corrosion Studies in Slurry Pipelines, *Proceedings, 2nd International Conference on the Hydraulic Transport of Solids in Pipes*, Warwick, September, Paper G2, 1972. pp. 15-24.

Raj, R.S. System Design for Hydraulic Transport of Filling Materials Through Pipelines into Mines. *Proceedings, 3rd International Conference on the Hydraulic Transport of Solids in Pipes*, Golden, May, Paper A3, 1974. pp. 23–37.

round, G.F. and El-Sayed, E. Pulsating flows of solid liquid suspension-bentonite-clay water suspensions. *Journal of Pipelines* vol. 5 1985. pp. 95–106.

Sive, A.W. and Lazarus, J.H. Literature Review for the Design of Backfill Slurry Pipelines, *Hydrotransport Research Report* 88/138, University of Cape Town. 1988.

Verkerk, C.G. Hydraulic Transportation as Applied to Backfilling in the South African Mining Industry. *Proceedings, 9th International Conference on the Hydraulic Transport of Solids in Pipes*, Rome, Paper F4, 1984. pp. 281–289.

◆