Backfill pipeline distribution systems—design methodology review

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ABSTRACT Despite the technology for designing backfill distribution systems being mature, a recent survey of Canadian backfill operations reveals that the majority of underground backfill system failures relate to the distribution system (blockages, pipeline bursts, and hammering). While some of the failures may be related backfill quality control, the majority of the problems are likely related to the design of the backfill distribution system.

This paper presents a review of the design process for backfill distribution systems, highlighting the differences between hydraulic and paste fill systems.

KEYWORDS Backfill, Paste, Slurry, Distribution

INTRODUCTION

In a recent survey of Canadian underground backfill practice, De Souza, Archibald, and Dirige (2003) report that over 55% of backfill system failures relate to the distribution system. As shown in Figure 1, these failures are due to:

- plugs (blockages) in pipelines and boreholes (35% of total failures and 63% of distribution system failures);
- pipeline bursts (12% and 22%, respectively); and
- pipe hammering (8.5% and 15%, respectively).

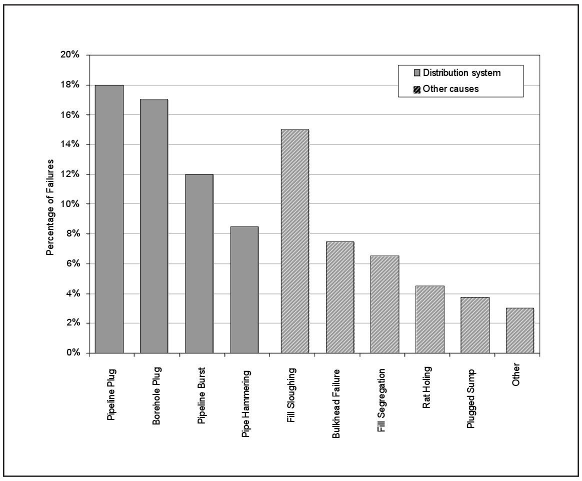

Fig. 1. Canadian backfill failures (De Souza et al., 2003).

Considering the maturity of backfill system technology, this high incidence of failures attributed to distribution systems should be considered unacceptable.

Some of the blockage incidents are likely to be related to the supply of out-of-specification backfill to the distribution system. This issue can be tackled by implementing more stringent quality control measures at the backfill plant.

The causes of the remaining distribution system-related failures may in many cases be related to "designed in" flaws in the system, i.e. there may be fundamental design problems with the system that may not be possible to resolve through changes to operational practice. These design flaws can arise because of two factors:

- an incomplete understanding of the backfill flow behaviour properties; and
- limited knowledge regarding the hydraulic behaviour of pipeline systems.

This paper addresses these issues.

BACKFILL DISTRIBUTION SYSTEM REQUIREMENTS

Before addressing backfill flow behaviour and pipeline hydraulics, it is worth reviewing the requirements and expectations of a backfill distribution system:

- The system must operate in a reliable and safe manner and not expose mine personnel to operational hazards.
- The system must deliver the flow rate or tonnage to a number of different locations and levels within the mine. Typically, the distribution piping is extended as mining operations proceed and the delivery flow rate should remain within fairly narrow limits.
- The system should operate without any blockages.
- The piping system should not fail due to excessive pressures or worn piping. Importantly, the piping should wear at a predictable rate to enable the effective planning and execution of pipe replacement schedules.

A well-designed system will meet these requirements, with the proviso that the backfill quality is within the defined limits.

BACKFILL PROPERTIES AND FLOW BEHAVIOUR

BACKFILL TYPES

There are two predominant backfill types[1]:

- Hydraulic or slurry backfill generally comprises deslimed metallurgical tailings, imported sand, or a combination of the two materials. Hydraulic backfill has a relatively high permeability and thus drains and consolidates rapidly on placement. In some cases, cement or a binder is added to increase the backfill strength. Due to the settling nature of the backfill, it is necessary to transport the backfill in the turbulent flow regime to avoid settlement during transport.
- Paste backfill (paste fill) is produced using total metallurgical tailings plus cement or a binder. Sand or aggregate may be added to improve the backfill strength. Paste fill produces little or no bleed water after placement. Most pastes can be characterized using the Bingham Plastic rheological model. Pastes are transported in laminar flow.

SLUMP TEST

The standard 300 mm concrete slump cone has become the industry standard for paste plant quality control and communicating paste properties (e.g., 150 mm or 6 in. slump paste). High slump values indicate low rheology or "viscosity," while low values indicate a "stiff" paste. The typical range of slump values used in paste fill applications is 150 mm to 250 mm, as illustrated in Figure 2.

The slump test can only be meaningfully applied to paste backfill, i.e. it is not applicable for hydraulic backfill.

Together with an empirical test database, the slump test can provide a preliminary assessment of the paste pipeline flow behaviour for conceptual designs. However, the accuracy is not suitable for final design, specification, and control of a pipeline system.

Figure 3 compares measured pipeline pressure gradients for cemented pastes produced using total tailings from three base metal mining operations. The following points are noted:

- The pastes from Mines A and B have similar slumps and similar pressure gradients, although it could be expected that the pressure gradients for Mine B would be lower than the data for Mine A due to the higher slump. For both these pastes, the pipeline pressure gradient is relatively insensitive to flow rate. This has important implications for the hydraulic design of the distribution system.
- The Mine C paste has significantly higher pipeline friction losses which are sensitive to relatively small changes in slump. If the system had been designed using an empirical correlation based on data from Mine A or B, the system would not meet its design duty.
- An important point to consider is the effect of shear on the paste properties. Figure 4 illustrates the slump of a paste produced using a thickener before and after shearing. Any test work for the design of paste distribution systems should be conducted using fully sheared material.

FRICTION LOSS VERSUS FLOW RATE

Figure 5 shows the variation of pressure gradient with flow rate for typical hydraulic fill and 200 mm slump paste fill in a 150 mm pipeline.

The friction loss for a typical paste is much greater than hydraulic fill for an equivalent pipe size and velocity. It is also important to notice that the hydraulic fill pressure gradient is much more

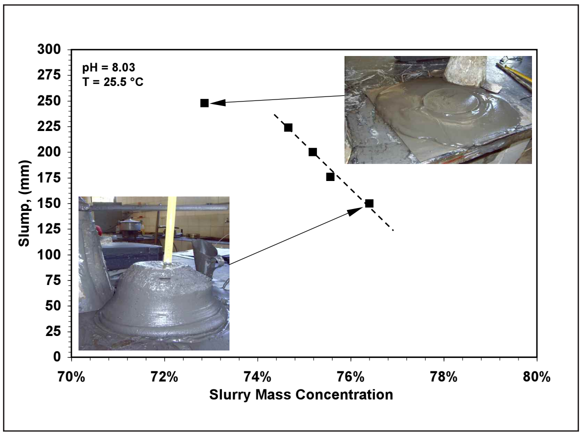

Fig. 2. Slump versus concentration (gold tailings).

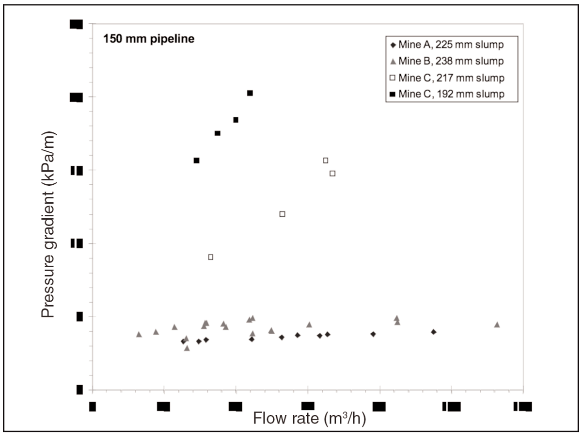

Fig. 3. 150 mm pipeline pressure gradient data.

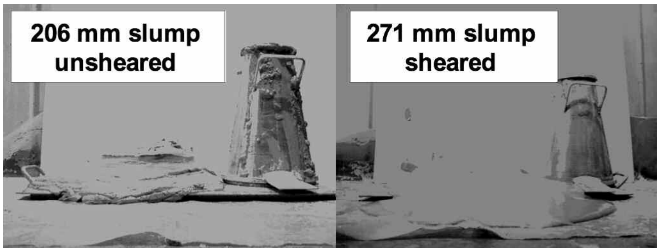

Fig. 4. Effect of shear on paste slump.

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[1] Backfill types that do not fall into this classification are generally applications where material is being disposed of underground for environmental reasons and the backfill is not an integral part of the mining operation.

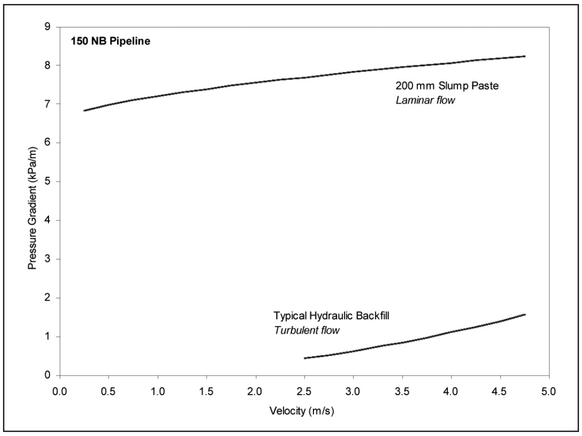

Fig. 5. Hydraulic and paste backfill pressure gradient curves.

Fig. 6. Laminar flow settlement in paste fill pipe.

sensitive to changes in flow rate than the paste fill pressure gradient. For example, at a velocity of 3 m/sec., a 10% increase in flow rate results in a 21% increase in the hydraulic fill pressure gradient, but only a 1% increase in the paste fill pressure gradient. This has a marked bearing on the stability of the operating point as discussed later in the section on hydraulic design of backfill distribution systems.

LAMINAR FLOW SETTLING

Some mines have experienced operational problems related to the settlement of coarse particles in cemented high-slump paste fill lines, as shown in Figure 6. This phenomenon is discussed by Cooke (2002).

Generally, laminar flow settling should not be a problem for pastes with a slump of less than 200 mm. Previous work suggested that the minimum pressure gradient required to ensure transport of settled particles in laminar flow was in the range of 1 to 2 kPa/m. Gillies, Sun, Sanders, and Schaan (2007) have investigated this issue in more detail and propose that the criterion for transport be based on the ratio of the mean wall shear stress to the mean surficial particle stress.

TEST WORK

Generally, sufficient knowledge is available on the flow behaviour of slurry backfills, allowing design and implementation to proceed based on laboratory scale test work.

Test work is required to establish the flow behaviour of paste mixtures. For preliminary investigations, this work can be conducted in laboratories using slump tests, viscometers, and small scale pipe loops. However, for final engineering and specification of the system, pipe loop tests should be conducted on site. The following points should be considered:

- The pipe loop tests should be conducted in at least two pipe diameters, although three is preferable, so that possible slip effects can be quantified. One of the pipe diameters should be the size anticipated for the distribution system.
- The paste should be as representative as possible. This includes tailings sampling, production method (sedimentation dewatering or filtration), flocculant type and dosage, cement/binder type and dosage, and shear state as discussed above.
- Ideally, to minimise particle degradation effects, once through pipe loop tests should be conducted instead of using a recirculation system. This is more important for coarse particle paste and tailings-aggregate mixtures.

BASIC PIPELINE HYDRAULICS

This section introduces the basic slurry pipeline hydraulics required for analyzing and designing a backfill distribution system.

BERNOULLI'S EQUATION

Bernoulli's equation, or the mechanical energy balance, applied across two sections of a pipeline system yields:

$$\frac{V_1^2}{2g} + z_1 + \frac{p_1}{\rho_m g} + \Delta H_p = \frac{V_2^2}{2g} + z_2 + \frac{p_2}{\rho_m g} + \Delta H_f \qquad (1)$$

where: V = mean pipeline velocity (m/s); g = gravitational acceleration (m/s^2); z = elevation (m of slurry); p = pressure (Pa); ΔH_p = head input by pump (m of slurry); ΔH_f = friction losses (m of slurry); and 1,2 subscripts refer to the upstream and downstream sections, respectively.

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[2] Strictly, the velocity head term in Bernoulli's equation is only correct for turbulent flow of Newtonian fluids. For laminar flows and non-Newtonian mixtures, a kinetic energy correction factor should be applied to correct for the velocity distribution. As the velocity head term is generally small, this correction is neglected for most engineering calculations.

The units of each term in Bernoulli's equation are Joules per Newton, generally referred to as "head" and expressed in metres of slurry[2].

Figure 7 illustrates Bernoulli's equation applied to a constant diameter pipeline system. The following terms are defined:

- Hydraulic head—the height to which the mixture being conveyed in the pipeline would rise in an open stand pipe as a result of the pressure in the pipe.
- Hydraulic grade line—a line drawn through the hydraulic heads along the pipeline.
- Hydraulic gradient—the slope of the hydraulic grade line (represents friction loss due to flow through the pipeline).
- Energy line—represents the total energy in the flow expressed in metres of the liquid being transported. The energy line lies $V^2/2g$ above the hydraulic grade line.
- Static head—the elevation difference between the liquid levels at the suction and discharge ends of the pipeline system.
- Total pump head—the total pump head is the difference between the energy line levels at the pump.

HYDRAULIC GRADE LINES

As the velocity head terms are usually very small compared with pressure and elevation head terms, the velocity head is generally neglected. The resulting diagram, shown in Figure 8, is referred to as a hydraulic grade line plot.

PLOTTING CONVENTIONS

There are two conventions for the x-axis of a hydraulic grade plot:

- The horizontal axis is the actual pipeline length, as shown in Figure 9. This is the standard convention used for slurry pipeline systems. For a constant diameter pipeline, the hydraulic grade line is a straight line on the plot.
- The horizontal axis is the true horizontal plan or map distance along the pipeline route. This alternate method is not preferred as the hydraulic grade line is not a straight line on the plot.

The y-axis is always plotted as elevation expressed in metres of slurry.

For overland pipelines, the x and y axes will be plotted at different scales, resulting in some vertical exaggeration of the plot. For underground backfill pipelines, it is preferable to use equal horizontal and vertical scales. If this is done for a standard hydraulic grade line plot, a vertical pipeline plots with a 45 degree slope on the hydraulic grade line.

HYDRAULIC GRADE LINES FOR ENGINEERING APPLICATIONS

Figure 10 shows an engineering hydraulic grade line plot:

- The hydraulic grade line is drawn for the design and maximum steady state conditions. In some cases, it may also be valuable to plot the hydraulic grade line when pumping water, as this will represent the minimum of the range of steady state operating conditions.
- The hydraulic grade line should also be developed for conditions during system start up and shut down.
- The envelope of pressures generated due to transient conditions is also generally shown on the hydraulic grade line plot.
- The pipeline pressure rating expressed in metres of slurry is presented on the hydraulic grade line plot. This line is referred to as the maximum allowable operating pressure (MAOP) and the hydraulic gradeline is not permitted to lie above this line. Generally, two MAOP lines will be indicated: one for steady state conditions and the other for transient conditions.

SYSTEM CURVE

A system curve, shown in Figure 11, is a valuable tool for establishing the operating stability of a system. The pipeline friction losses and head generated by the pump are plotted as a function of flow rate. The intersection of the two curves determines the system operating point.

HYDRAULIC DESIGN OF BACKFILL DISTRIBUTION SYSTEMS

DESIGN PROCESS

The basic process of designing a backfill system entails the following:

- Establish the design duty specification for the system in consultation with the owners and operators. This must take into account any planned variations in production during the envisaged system life.
- Determine the pipe routing. Generally, the route is largely dictated by the mine layout, although there may be scope to optimize the routing, as discussed in the following section.
- Establish the backfill flow behaviour characteristics. This will entail laboratory testing at a minimum and, for paste systems, onsite loop tests are recommended.
- Perform the hydraulic analysis of the system considering all envisaged operating conditions. The output of this analysis will be the preliminary piping specification. Other hydraulic components such as pumps, chokes, and valves will also be specified at this stage.
- Undertake the mechanical design of the piping and piping support system. Depending on the output of this activity, changes to the piping specification may be required.
- Specify operating, monitoring, and maintenance procedures for the backfill distribution system.

PIPELINE ROUTING

As noted above, the distribution piping routing is largely defined by the mine layout. However, there are usually some opportunities for optimizing the piping layout and the following issues should be considered:

- Ideally, the slope of the piping should reduce along the distribution system, i.e. vertical down sections should be at the start of the distribution system, with horizontal piping towards the end of the system.
- It is preferable to have a series of vertical piping sections instead of a single vertical section. This reduces the pipeline operating pressures.
- Pipes may be installed in shafts to reduce installation costs, although this is generally not preferred due to safety considerations.
- Inter-level boreholes can be used to reduce the total pipeline length and to optimize the pipeline profile.

HYDRAULIC ANALYSIS – BALANCED GRAVITY FLOW

Consider a gravity backfill system with a 500 m vertical elevation change and a total pipeline length of 1,500 m.

Figure 12 shows the pipeline system curves for hydraulic backfill in three pipe diameters (100, 125, and 150 mm). As this is a gravity system, there is no

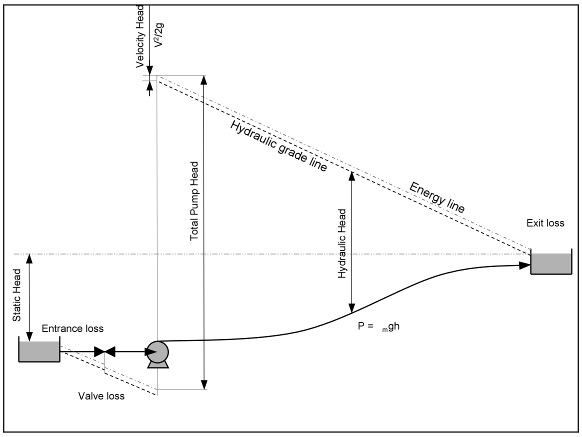

Fig. 7. Bernoulli's equation applied to a slurry pipeline system.

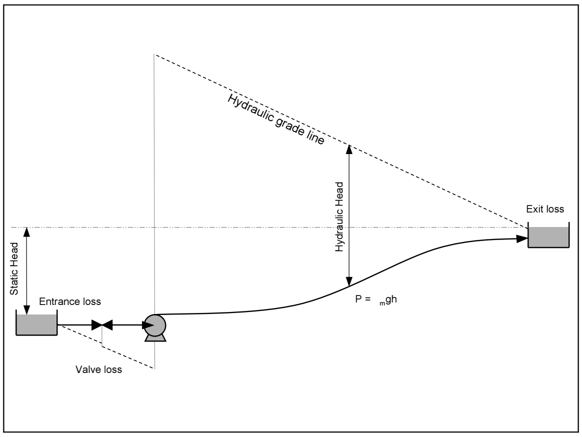

Fig. 8. Hydraulic grade line plot.

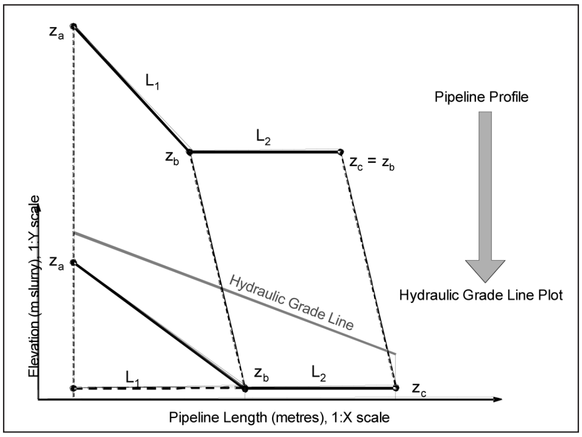

Fig. 9. Standard hydraulic grade line plotting convention.

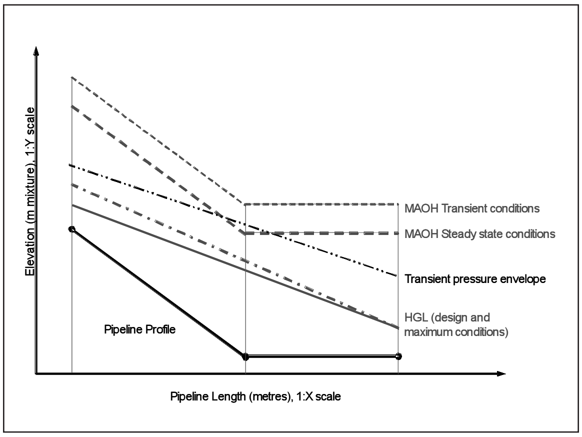

Fig. 10. Engineering hydraulic grade line plot.

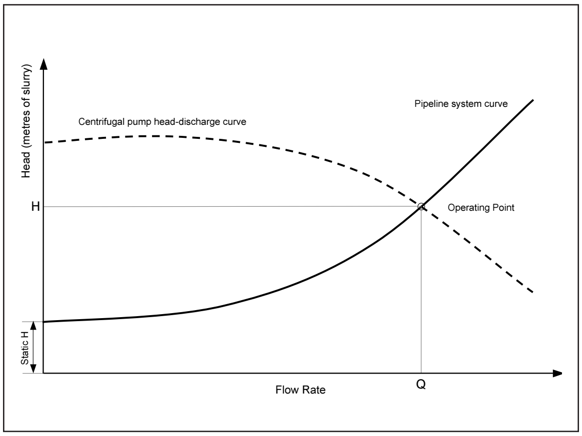

Fig. 11. System curve.

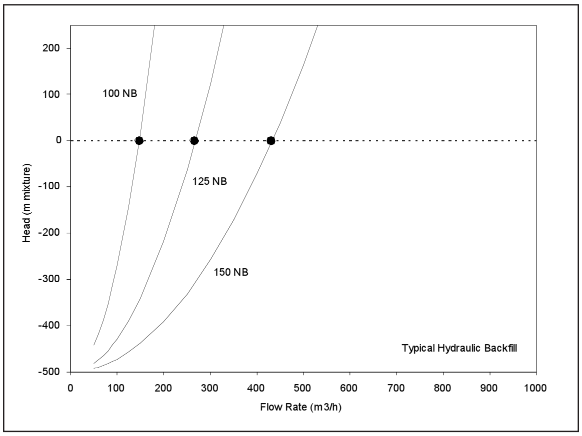

Fig. 12. System curve: hydraulic backfill – balanced flow.

pump curve and the operating flow rate for each pipe size is the intersection of the pipeline friction curve and a horizontal line drawn at zero head. For each pipe size, there is a distinct operating flow rate, termed the balanced flow rate. The designer chooses the pipe size, or combination of pipe sizes, that best meets the system duty flow rate.

Figure 13 illustrates the same case for paste fill in 125, 150, and 200 mm pipe diameters. In this case, there is only an operating point for the 200 mm pipeline at a high flow rate. There is no intersection for the 125 mm and 150 mm pipelines and, theoretically, there will be no flow through these pipelines.

This example illustrates a fundamental hydraulic difference between hydraulic and paste fills: stable gravity flow can be achieved with hydraulic systems, while paste systems generally require a pump to ensure stable operation.

HYDRAULIC ANALYSIS – PUMPED SYSTEMS

Figure 14 shows how adding a positive displacement pump to the system results in possible operating points for the 125 mm and 150 mm pipelines. The intersection point with the 125 mm pipeline curve is not ideal as this is at the limit of the pump's discharge pressure capacity. The intersection with the 150 mm pipeline represents a better operating point as it is not at the limit of the pump pressure capacity and so there will be some tolerance for variations in the backfill properties.

Operating the system with the 200 mm pipeline will result in negative pump discharge pressures. This will cause operational problems with the pump and this condition should be avoided.

Figure 15 presents the hydraulic grade line plot for the above example (150 mm pipeline at 500 m^3/h). The pressure at any point along the pipeline can be determined by multiplying the hydraulic head (elevation difference between the hydraulic grade line and the pipeline profile) by the paste density and gravitational acceleration.

The hydraulic grade line shown in Figure 16 considers the effect of an increase in the pipeline friction losses. In this case, a 10% increase in pipeline friction results in a 35% increase in the pump discharge head requirement. When specifying a pump for a paste system, it is important that the full range of expected operating conditions is considered (this includes start and shut down conditions which can represent the most adverse pump duty).

HYDRAULIC ANALYSIS – SLACK FLOW AND FREE FALL

Figure 17 illustrates an alternate pipeline profile which results in a hydraulic grade line being below the pipeline profile over a length of route. This indicates negative pipeline pressures. If the pressure falls

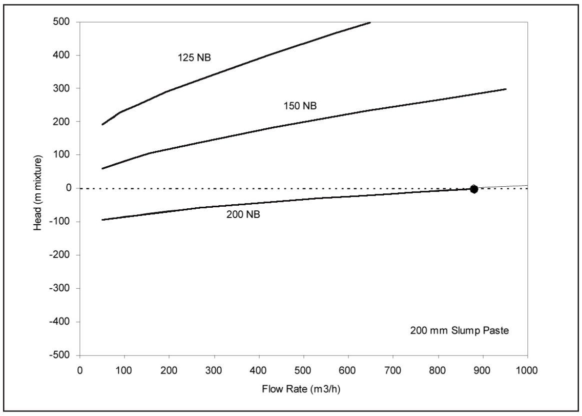

Fig. 13. System curve: paste fill – balanced flow.

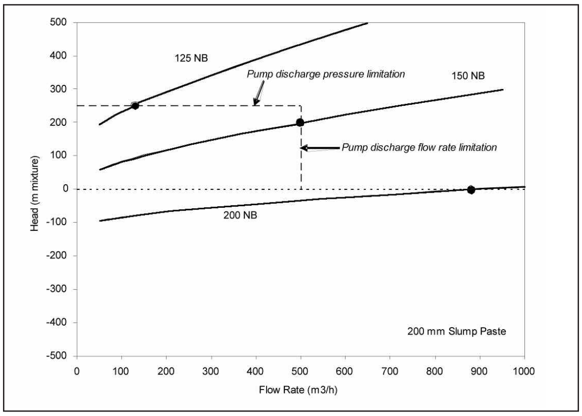

Fig. 14. System curve: paste fill – pump assisted.

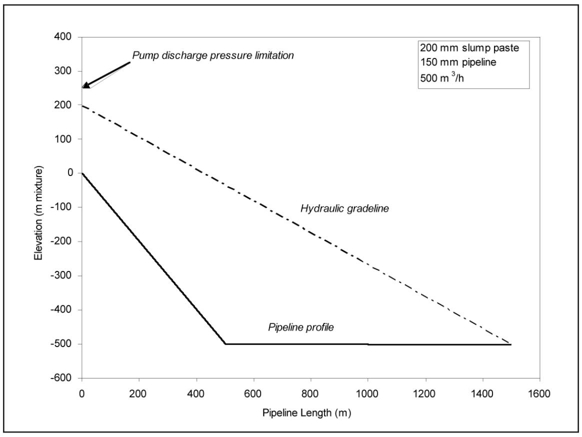

Fig. 15. Hydraulic grade line: paste fill – pump assisted.

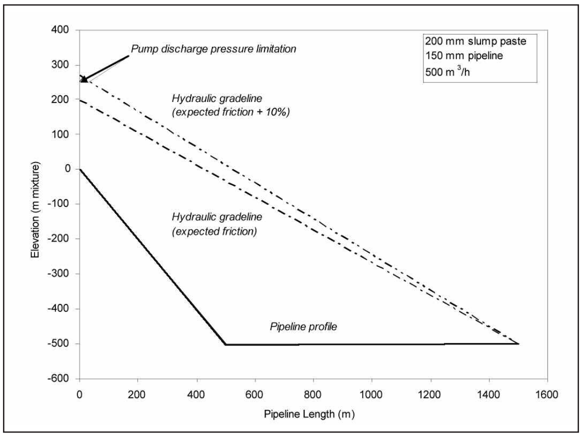

Fig. 16. Hydraulic grade line: paste fill – sensitivity to friction loss.

below the vapour pressure of the mixture, slack flow or free fall will occur:

- Slack flow occurs in sloping pipelines. The backfill will flow with a free surface in the slack flow section, i.e. open channel or launder flow. If the pipeline slope is steeper than the hydraulic gradient when the pipeline is flowing full, the backfill will accelerate until it reaches a velocity such that the friction losses equal the pipeline slope. This velocity may be an order of magnitude higher than the pressurised flow rate, resulting in severe erosion of the pipeline invert.
- Free fall occurs in vertical pipelines. Extremely high velocities can occur in free fall conditions, resulting in rapid erosion and failure of the piping, as described by Paterson, Cooke, and Gericke (1998).

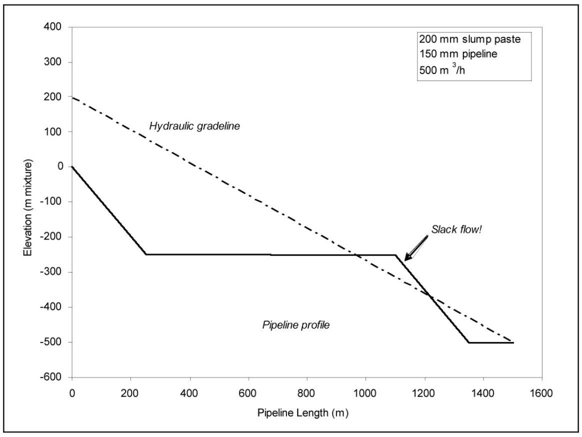

Fig. 17. Hydraulic grade line: paste fill – slack flow. Note that this plot is not an accurate representation of the hydraulic grade line under slack flow conditions. It is used to indicate that slack conditions will exist; corrective design measures are then implemented to avoid slack flow.

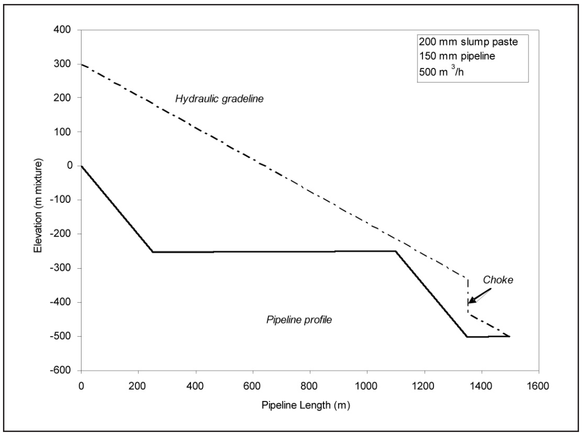

Fig. 18. Hydraulic grade line: paste fill – installation of choke station to avoid slack flow.

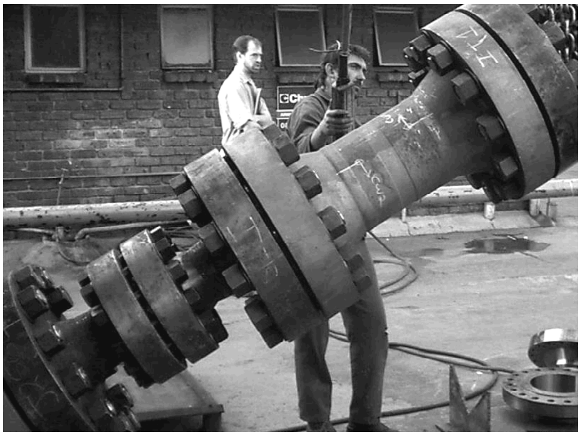

Fig. 19. Pressure test of energy dissipater used for backfill choke stations.

To avoid slack flow or free fall conditions, the hydraulic grade line in the vicinity of a high point must be raised. This is done by increasing the downstream friction losses either by installing smaller diameter piping or a choke station. Figure 18 illustrates how the installation of a choke station corrects the hydraulic grade line so that slack flow conditions are avoided.

An energy dissipater used in backfill choke stations is shown in Figure 19.

FLUSHING

Backfill pipelines are generally pre-flushed with water or "slicked" with low concentration paste. Post flushing can be a combination of water flushing, air injection, and pigging.

These conditions must be evaluated as part of the hydraulic design process

BACKFILL QUALITY CONTROL

The proper performance of a backfill distribution system is dependent on the backfill properties being within the specified range. To minimize the risk of operational problems associated with "out of specification" backfill, consideration should be given to the installation of a pressure gradient loop on surface. By measuring the flow rate, density, and pressure loss across and straight horizontal length of pipe, an indication of the backfill properties can be determined. This allows corrective measures to be implemented at the backfill plant or, if necessary, to take pre-emptive action to avoid a blockage of the distribution system.

CONCLUSION

A key cause of backfill distribution system operational problems and failures may be related to "designed in" flaws in the system. A good understanding of backfill flow behaviour and pipeline hydraulics is required to design systems that operate safely and reliably.

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