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Hydraulic design of a thickened tailings gravity discharge and distribution system

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Abstract

It has become common practice for mining tailings to be thickened before being deposited in a tailings storage facility (TSF) to increase water reclamation, reduce overall footprint and comply with current environmental regulations. TSFs that impound thickened tailings (TT) typically consist of distribution systems along the TSF embankments or in the basin's perimeter, defined by a deposition plan. These main deposition systems include linear distribution discharges or manifolds, a pressurised radial distributor or a distribution box with a series of spigots discharging over the TSF.

Other deposition options may be considered for conditions where the site's topographic surface is relatively flat or the basin is somehow constrained to allow for perimeter filling. For example, TT can be deposited within a TSF basin with a flat topography using spigots located on elevated discharge platforms that are relocated throughout the TSF's life span.

TT can either be discharged onto the TSF surface from the top or the bottom of these discharge platforms. The discharge platform is susceptible to abrasion when TT is discharged from the top of the platform. Alternatively, a hydraulic design challenge is introduced when TT is discharged from the bottom of the platform with the aid of gravity as the rising tailings could block the exit as deposition progresses.

This paper provides a methodology that has been applied in large tailings projects with gravity distribution and discharge systems, and a design guide for its application in the industry.

Keywords: *thickened tailings, gravity flow, tailings transport, spigots*

1 Introduction

Mine waste management is probably the greatest risk and one of the most important challenges that the mining industry faces today. Tailings dewatering, transport and deposition in a tailings storage facility (TSF) has become one of the most important aspects in mining projects and operations. The industry has been increasingly subjected to stringent regulations and international guidelines while being constantly pushed to seek the reduction of the impacted TSF footprint for compliance with environmental regulations in the jurisdictions that it operates. Mining environmental regulations are becoming increasingly more restrictive with both existing and proposed mining operations, especially with the increased ability to profitably exploit large, very low-grade resources that were previously considered uneconomic. This advancement takes into consideration operational, environmental, technical, financial, risk and social issues (Riquelme 2020). The industry has been able to progress by increased process efficiencies and economies of scale while seeking long-term solutions for mine waste and water management. The latter is the biggest challenge in tailings storage, for both wet and dry environments. Thus the application of appropriate strategies and procedures leads to the most varied arrangements of tailings disposal systems.

If the objective is to reclaim as much process water as possible then the challenge calls for a multidisciplinary approach. From the tailings dewatering processes and hydraulic transport perspective there are the options of conventional tailings, cycloned tailings including a coarse underflow and slimes overflow, thickened tailings

(TT), and a range of paste and filtered tailings. There are several ways and means by which tailings are can be safely stored, depending on many factors such as index and rheological properties of the tailings, solids concentration, production plans, environmental conditions and the topographical characteristics of the site.

TT is usually stored in a TSF through turrets and spigots mainly placed in an extension of the perimeter of the dam defined by a deposition plan to maximise the use of the surface and depth of the basin that receives them, and is contained at the outlet by an earth wall strategically located to reduce construction volumes.

The search for sites with optimal conditions for the placement of a tailings deposit in the vicinity of the process infrastructure invites the consideration of other options. For example, there are cases where the site topography is flat or semi-flat and there is no extensive and deep basin that allows perimeter filling, and the growth strategy seeks not to increase the height of the walls at an accelerated rate. In such cases there are several ways to proceed with the deposition plan and decide where to optimise the site with methodologies including storage plots, elevated deposition-forming tailings cones and semi-cones, and discharging of the material on a clean surface or where the tailings have already been deposited previously.

Furthermore, the mining industry has been forced to consider expansions of their existing impoundments in the last decade, given the scarcity of sites for new TSFs. A typical support surface arrangement for TT uses a system of platforms and consecutive deposition ramps. These platforms are repositioned and relocated or raised in altitude to satisfy their functionality of transport and elevated tailings discharge, according to the deposition plan throughout the life of the TSF. Furthermore, these platforms are constructed directly over the tailings by controlled placement of massive quantities of engineered fill material.

This paper introduces the hydraulic design of a free surface gravity discharge system for TT and its distribution and disposal system, accompanied by complete hydraulic requirements.

2 Main tailings distribution systems

The achieved solids concentration of the thickener underflow depends on the tailings material, its settling rate and the type of thickener selected for the project. Usually the decision is driven by multiple factors including the overall cost of the tailings management system, the make-up water supply and/or the requirement for consistency of safe depositions at the TSF. Once the type of thickener for the project has been selected, the TSF designer has very little margin to improve the material and rheological properties the thickener underflow, and can only focus on achieving the optimum operating performance. Therefore, the only other tool in the hand of designers and operators than can be improved is the slope of the deposition beach with the flow rate and discharge system.

Splitting the total tailings flow into several discharges to the TSF will result in the formation of a steeper beach slope profile. In addition, uniform distribution and discharge of tailings into the TSF is a key element in filling the storage space evenly and optimising the effective storage capacity of the TSF. However, there is a limitation on the number of flow splits that will be possible at a given site, depending on the geometry of the storage and the filling method, as separate flow streams will tend to merge on the beach if the discharge spigots are too close to each other or leave unfilled spaces if the spigots are too far apart (Pirouz et al. 2020). The industry has adopted three different spigot arrangement systems for flow splitting: linear distribution discharge or manifold, pressurised radial distributor and distributor box.

2.1 Linear distribution discharge or manifold

Linear distribution discharge or manifolds feeds tailings through a single line which in turn feeds a main distribution manifold. From this manifold, branches and spigots discharge the tailings to the TSF. The tailings discharges are regulated using ceramic rings or pinch valves. This solution typically operates on the safe side without high operational risks because it has been based on proven designs in the industry (Bazán 2020). This system can be used for conventional and TT discharge, and the energy to ensure discharge through the spigots comes from the head pumps. It allows the distribution of flows of most sizes (see Figure 1).

Figure 1 Linear distribution manifold

2.2 Pressurised radial distributor

Pressurised radial distributors have a very simple hydraulic and operational design that includes pumping the entire tailings flow to the distributor vessel through a single pipe. From this vessel, the spigots discharge the flow into the TSF. The radial distribution of this vessel results in equal flow distribution and discharge from all outlets at all flow conditions. The system adjusts automatically and does not require regulating valves or the continuous presence of an operator. Its use is preferred when the central discharge method is used, and the edge of the discharge platform is not too far from the distributor. This system can be used for conventional and TT discharge, and the energy to ensure discharge through the spigots comes from the head pumps. It is not recommended for handling large flows that require a large vessel size, due to potential internal sedimentation and high pressures (see Figure 2).

Figure 2 Pressurised radial distributor

2.3 Distributor box

Distributor box systems consider a single tailings feed that discharges into the distributor box at atmospheric pressure. From this box, the tailings are discharged into the TSF through independent gravity discharge lines. The design considers regulation by pinch valves for an equal discharge over the TSF under certain conditions. Its use is not recommended for non-Newtonian TT with high rheology since the tailings lose all the energy provided by the pumping system when discharged into the box. Thus, a high initial energy is needed for the tailings to start flowing through the gravity discharges due to the yield stress and the viscosity of the fluid.

This high initial energy is not always available in the system. Furthermore, computational fluid dynamics studies have shown that the distribution of tailings in the discharge is uneven because there is no pressure at the beginning of the discharge. The energy balance will typically facilitate the central discharge but not the discharge through the end lines. This system can handle large flows in the mining sub-sectors (see Figure 3).

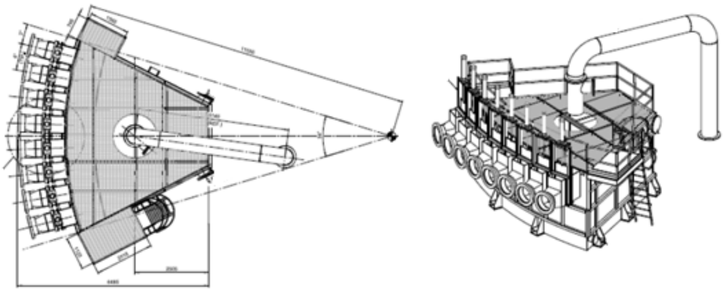


Figure 3 Distributor box

3 Gravity discharge

Gravity runoff presents enormous challenges, especially the steep runoff slope for non-Newtonian tailings with high rheological properties, regardless of the tailings distribution system selected. In many instances for non-Newtonian TT, the slopes required for an adequate flow turn the distribution system into a cascade of unstable flows, roll waves and hydraulic jumps. These large flows often involve hydraulic jumps and instabilities that could turn into slug flow when not properly designed.

A solution methodology that has been applied in large-scale complex tailings projects is presented in this paper. The design was approved and is part of the engineering solution for a large tonnage copper tailings project located in northern Chile. This methodology has been proven to ensure the gravity flow of non-Newtonian TT in a safe way from discharge platforms inside the TSF basin or from any place where the discharge is conducted with a high slope.

4 Methodology for hydraulic design of a TT gravity discharge system

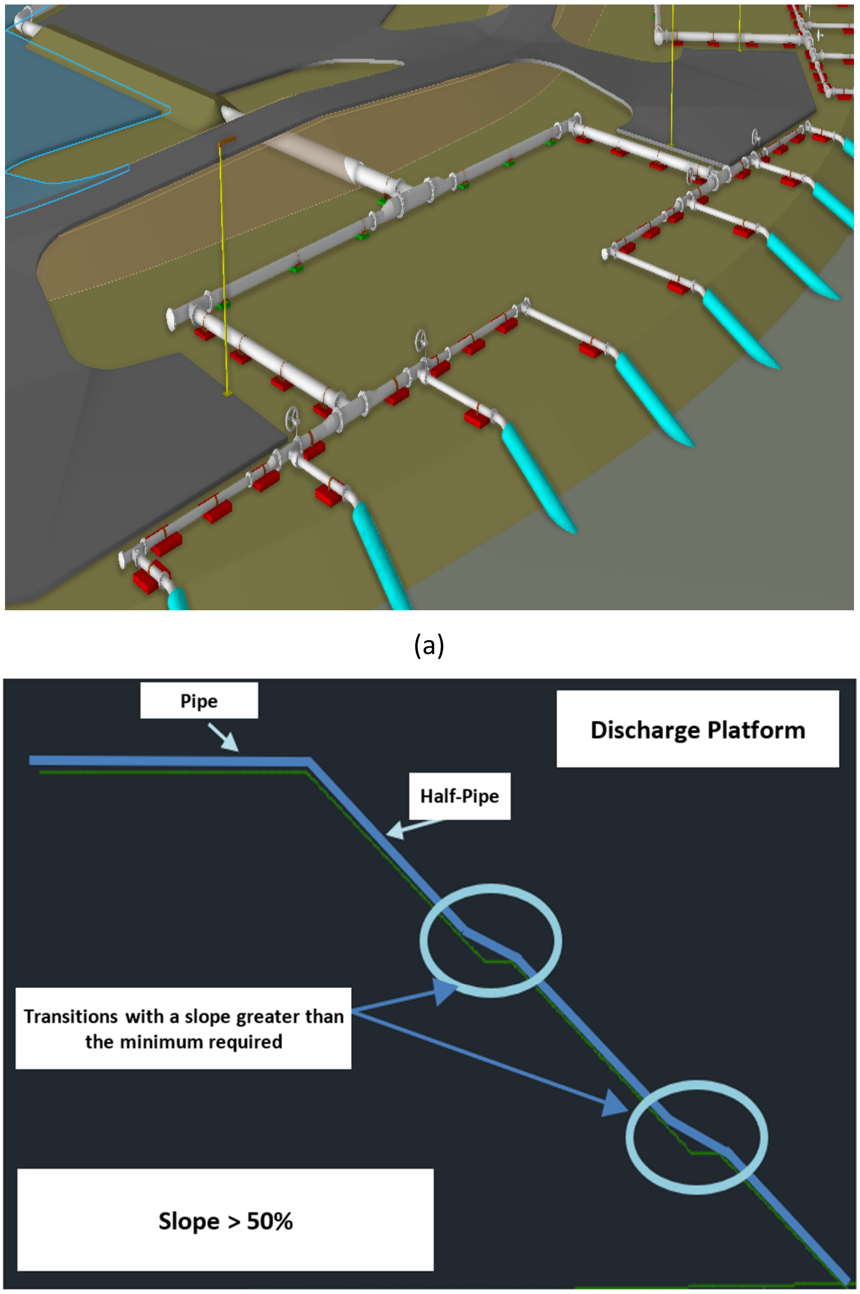
4.1 Hypothetical case study

The following hypothetical case study is considered to show the methodology used for gravity discharge of non-Newtonian TT on steep slopes.

Consider the discharge of high-flow tailings through a linear distribution discharge system and a high-altitude platform that is located within the TSF basin, and which has a steep slope (>50%) and a long length. The TT can be discharged from the top or bottom of these discharge platforms to the surface of the TSF. The discharge platform is susceptible to abrasion when TT is discharged from the top of the platform, while a hydraulic design challenge is introduced when discharging by gravity from the bottom of the platform due to the rising tailings level as deposition progresses.

The pressurised manifold considered feeds eight gravity lines into spigots. Each pressurised manifold has a symmetrical and compensated hydraulic design that allows each of the discharge lines to deliver the same nominal tailings flow (see Figure 4a).

The gravity discharge over the slope should allow the tailings to exit without obstruction as the deposit increases in height, in addition to avoid splashing or overflows that could wet the platforms and generate stability risks. Therefore, the design considers individual discharges over the slope through a half-pipe that allows the non-Newtonian tailings with high rheological properties to gravity run off on free surface and eliminates the risk of overflow (see Figure 4b).



(a)

(b)

Figure 4 (a) Pressurised manifold system; (b) Discharge line profile example

The hydraulic challenges presented by the proposed methodology are as follows:

- To maintain the pressurized discharge manifold so it is capable of discharging tailings equally on each of the gravity transport half-pipes located on the slope of the platform.
- To ensure a safe runoff for each of the tailings discharges that are driven by the half-pipes projected on the slope of the discharge platform, which must ensure a minimum slope to minimise runoff, a supercritical gravity driving regime and that the free surface of the fluid is stable.

4.2 Pressurised manifold design

The first step is to design the tailings distribution system. A single tailings feed and a symmetrical distribution manifold were considered for the hypothetical case, ensuring that the same equal flow is discharged from each spigot (see Figure 5).

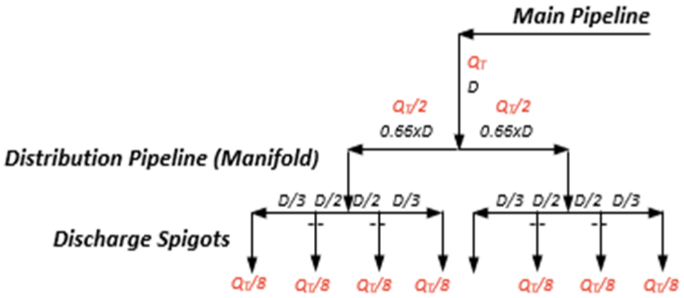


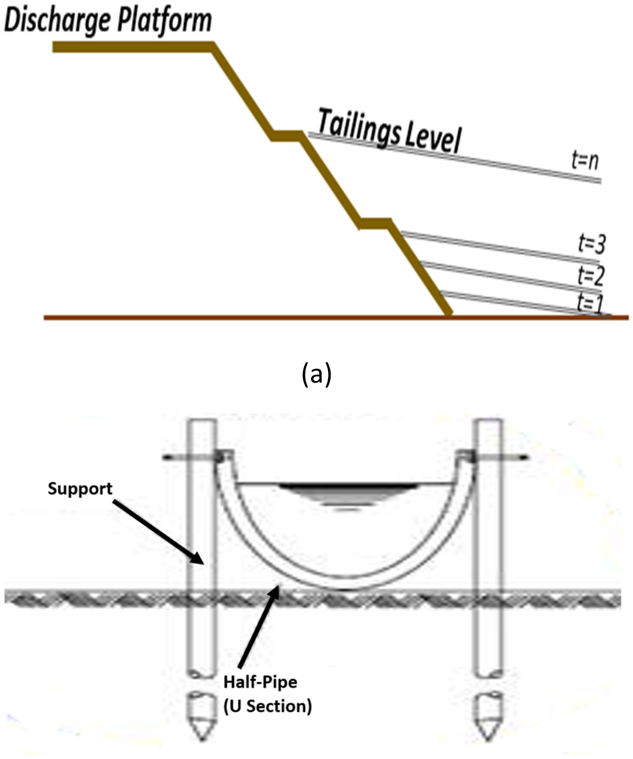
Figure 5 Pressurised manifold – tailings distribution system

The design of the pressurised manifold meets the hydraulic design criteria for non-Newtonian TT (Bingham plastic-type fluid), where the flow in each branch is turbulent with velocities greater than the laminar-turbulent transition. This is confirmed by using the Darby et al. (1992) model to estimate the unit head loss of the pressurized pipe system and the Thomas and Wilson (1987) method to ensure turbulent flow. In the latter, the laminar and turbulent flow curves are plotted for a range of velocities and the transition velocity is estimated at the point where they intersect.

4.3 Gravity discharge over the platform slope

The tailings should be discharged without hindrance as the deposit increases in height (see Figure 6a).

The tailings are discharged using half-pipes with an "U" cross-section (see Figure 6b).



(a)

(b)

Figure 6 (a) Simplified schematic of tailings deposit growth; (b) Half-pipe cross section (U section)

Gravity runoff for non-Newtonian TT with high viscosity and yield stress is not common in the industry, and a series of conditions must be met for the conduction to occur because of the fluid characteristics.

The proposed methodology considers the following verification parameters that guarantee that gravitational open channel runoff is possible without the risk of settling, and with a stable and free conduction surface:

<u>Step 1</u>: The minimum discharge slope is calculated.

The minimum slope for homogeneous or pseudo-homogeneous TT is expressed as:

$$S = \frac{f_N U^2}{2gR_H} \tag{1}$$

where:

S = slope (non-dimensional).

f_N = Fanning friction factor (non-dimensional), corrected, based on the experimental work of Pirouz (Pirouz & Williams 2007).

U = superficial or average flow velocity (m/s).

g = acceleration due to gravity (9.8 m/s^2).

R_H = hydraulic radius (m).

<u>Step 2</u>: The Froude number for Bingham fluids is calculated and verified by an iterative process.

The conduction must always be far from the critical depth so the operation in supercritical conditions is 1.2 times the value of the Froude number for a Bingham fluid, which is calculated according to Equation 2:

$$Fr_B = U\sqrt{\frac{1}{gZ_c}} \tag{2}$$

where:

Fr_B = Froude number for a Bingham flow (non-dimensional).

U = superficial or average flow velocity (m/s).

g = acceleration due to gravity (9.8 m/s^2).

Z_c = critical depth (m), calculated and corrected for non-Newtonian flow (Shu & Zhou 2006):

$$Z_c = \sqrt[3]{\frac{C_0 \times Q^2}{b^2 \times g}} \tag{3}$$

where:

C_0 = Factor for calculation of critical depth of a hydraulic jump for a Bingham flow (non-dimensional)

For fully viscous flow, the measured C_0 must account for the ratio of yield stress to wall shear stress upstream of the hydraulic jump. Using the ratio of yield stress to wall shear stress (ξ) to define C_0:

$$C_0 = \frac{3}{5}\left[\frac{8+17\xi+20\xi^2}{(1+\xi+\xi^2)(2+\xi)^2}\right] \tag{4}$$

For inviscid flow C_0=1

Q = Flow (m^3/s).

g = Acceleration due to gravity (9.8 m/s^2).

b = Surface width (m).

Step 3: The Vedernikov number should be verified in the event of high slopes and high velocities.

The Vedernikov number verifies the stability of the free surface given by the ratio of the relative celerity of the kinematic waves to the celerity of the dynamic waves. The Vedernikov number for unstratified flows can be evaluated in simple terms with Equation 5:

$$Ve = \frac{2b}{3WP}\left[\frac{U_m}{\sqrt{g z_m \cos k}}\right] \tag{5}$$

where:

Ve = Vedernikov number (non-dimensional).

WP = Wet perimeter (m).

b = Surface width (m).

U_m = Average velocity in channel (m/s).

g = Acceleration due to gravity (9.8 m/s^2).

z_m = Average depth of channel (m).

k = $\tan^{-1}(Sf)$.

Sf = Friction slope (non-dimensional).

If Ve<1, the regime flow is stable. If Ve>1, the flow is unstable as the mass-transporting waves (kinematic) move faster than the energy-transporting waves (dynamic).

In this case,

> *'Any wave created in the facility will tend to amplify up to a maximum height of 1.65 times normal depth, given a suitable length of run. For open channels, consider at least 1.7 times normal depth to establish freeboard requirements' (Abulnaga 2021).*

Step 4: Check and iterate over the diameter of the half-pipe to meet the minimum slope, the Froude number and the required freeboard considering the Vedernikov number.

Finally, the pipe required for the engineering solution is obtained when all design parameters are met.

5 Conclusions and recommendations

The scarcity of greenfield sites for new TSFs has provoked mining industry operators to continue to use existing conventional slurry impoundments. This is typically achieved by discharging TT directly above the formed slurry beaches using a system of platforms and consecutive deposition ramps from where the tailings are discharged. These platforms are repositioned, relocated and raised throughout the life of the TSF following the TSF's deposition plan. The platforms form steep slopes and long beach profiles, thus the discharge of non-Newtonian TT through their slopes is a constant hydraulic challenge.

As part of the design, filling of the TSF basin must be initiated from its topographic lows and discharge platforms must consider long slopes due to the large production scale. With these constraints and challenges as design limitations, an engineering solution is proposed for tailings to be transported by gravity through a half-pipe at all times. The gravity flow must always be transported at a runoff slope greater than that required by the system and the flow must be maintained completely at a supercritical level. This condition is to prevent sedimentation and clogging of the system. The design methodology also ensures that no splashes or overflows occur on the platform slope.

The hydraulic transport methodology presented in this paper can be used whenever non-Newtonian TT are produced. However, the methodology requires the tailings flow be gravity transported with a calculated minimum slope.

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