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Tailings Dam Mining, Theoretical Considerations, and Circular Economy: A Review

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Abstract

Mining in tailings dams has emerged as a strategic alternative for mining companies for both economic and environmental reasons. Owing to technological limitations in recent decades, many of these dams have high metal contents, emphasizing the need to evaluate the quality of these residues, especially considering the technological advancements in current concentration plants. An economic viability analysis associated with reusing these materials is crucial. From an environmental point of view, improving mining techniques for dams by considering both safety and feasibility is an advantageous option in decommissioning processes and alignment in the circular economy. In this context, representing these tailings in terms of grade quality and granulometry, as well as the associated contaminants, is essential. Geostatistical estimation and simulation methods are valuable tools for modeling tailings bodies, but they require a reliable sampling campaign to ensure acceptably low errors. From an operational perspective, tailings recovery can be conducted via dry methods, such as mechanical excavation, or hydraulic methods, such as dredging or hydraulic blasting. Dredging is a commonly used method, and cutter suction dredgers, which require pumping to transport fragmented material, are the most commonly used tools. In this paper, some practical applications of geostatistical methods for resource quantification in tailings dams will be discussed. Additionally, the main mining methods for tailings recovery in dams will be presented. Emphasis will be given to the dredging method, along with the key analysis parameters for sizing dredgers, pumps, and pipelines.

Keywords

Mining in Tailings Dams, Geostatistical Methods, Grade Quality, Dredging

1. Introduction

The mining industry has historically been an important supplier of infrastructure materials and inputs for technological developments that promote social wellbeing (Garbarino et al., 2018). To meet the growing global demand for ores, there has been an expansion in the mining of several commodities and advances in the development of more complex and lower quality mineral deposits. However, this expansion has not been accompanied by the development of techniques that allow for more efficient and sustainable production.

Given this scenario, the production of tailings and effluents from mining processes has grown substantially, requiring a greater number of deposition systems such as dams and tailings deposition ponds. According to data from 1743 tailings deposits around the world, the volume of material dammed in tailings deposits reached 44.5 billion m^3 in 2020 (Franks et al., 2021), and the projection is that by 2024, there will be an increase of another 10 billion m^3.

Wates et al. (2010) noted that "deactivated tailings dams will be the mineral resources of the future". Given the large number of tailings deposits around the world, this statement characterizes the efforts of the mining sector to transform tailings dams into valuable assets. In addition, some dams, especially those from the 1990s, contain relatively high contents of metallic materials because the mineral beneficiation processes of the day did not perfectly recover the target metals, which are ultimately lost in the tailings.

Ferrante (2014) noted that there has been greater investment in ore treatment technology over the years, where alternatives were sought to treat tailings and recover their metallic contents in particle size fractions that were previously discarded. In addition, as many of the high-grade reserves are close to exhaustion, there is a growing need to recover these types of tailings.

Studies involving revisiting tailings dams have two main interests: reprocessing for the recovery of metals and valuable elements and the integration of the recovered product in the industrial chain. The recovery of these elements would also mean a reduction in the volume of tailings dams, which is currently one of the greatest mining liabilities (Løvik et al., 2018).

Tunsu et al. (2019) noted that although the recovery of resources deposited as tailings has aroused great interest in the mining sector, these assets are highly vulnerable to market fluctuations, geotechnical risks and geological uncertainties inherent in the very nature of these deposits. Sarker et al. (2022) emphasized that it is necessary to adopt a multidisciplinary approach that integrates geochemical data, technological characterizations, the use of efficient beneficiation methods and the representative geological modeling of *in situ* resources for different elements. To this end, the path begins with sampling and chemical analysis to understand the distribution and nature of the sediments contained within these systems and to support the development of efficient mining strategies.

Another challenge in the recovery of these resources is the lack of studies that integrate all the data necessary for accurate evaluations. Most existing methods are based on data from geophysical estimation techniques combined with the average metallic contents of deposits and focus on specific aspects, such as the geochemical, physical and geotechnical characterizations of the systems (Karacan et al., 2023).

The main methods used in mining in aquatic environments, especially in dams, are hydraulic blasting, which is usually performed with pressurized water jets, and mechanical blasting, which is performed with conventional or amphibious excavators. In addition, dredging is a viable alternative because it allows for maximizing the recovery of mineral resources and reducing the environmental risks and impacts.

Therefore, this study reviews mining in dams from the perspectives of quantifying resources (geostatistical models) and assessing existing mining methods that can be applied in the recovery of tailings in dams.

In the following sections, regarding resource quantification in tailings dams, the main works that utilize geostatistical models for a better understanding of the chemical elements and grade distribution in the tailings body will be presented. For tailings recovery, the main mining methods will be discussed, highlighting their specific characteristics, advantages, and disadvantages. Subsequently, a more comprehensive approach to the dredging method will be provided, focusing on the particular aspects of sizing dredgers, pumps, and pipelines.

2. Quantification of Resources in Tailings Dams

Many studies, including those conducted by Espósito (2000), Santos (2004), Gomes (2009), Rezende (2013), Alves (2015) and Sousa (2020), have focused on characterizing the chemical quality and the granulometric analyses of tailings. The objective of these studies was to determine the most efficient route for mineral beneficiation processes and the most appropriate method for mining dams. These investigations highlighted a phenomenon known as hydraulic segregation in tailings dams, showing that the grain density, permeability and iron content decrease as the distance from the tailings discharge point increases.

Modeling the *in-situ* resources of tailings deposits is complex because they are highly heterogeneous systems. Historically, tailings deposition has been carried out in the form of sludge, leading to the formation of a sedimentary depositional structure characterized by particle stratification by density and grain size in relation to the deposition zones (Vick, 1990).

This condition has created zones of high and low content within the stratified structures, whereby heterogeneity can be intensified by exogenous temporal erosive processes, metal transport and precipitation (Vick, 1990; Lottermoser, 2010; Nikonow et al., 2019). This characteristic hinders the formulation of stationarity hypotheses essential for geostatistical modeling methods, which in turn results in a lack of information on the variables that impair the modeling processes (Parviainen et al., 2020).

The geostatistical modeling of mine tailings dams is crucial for understanding the spatial distribution of tailings deposit characteristics. It involves the application of statistical methods and geospatial techniques to analyze and represent the variability of the attributes present in tailings, including mineral concentrations, texture, and grain size. This integrated approach to geostatistical modeling in mining tailings dams plays a key role in the sustainable management of these structures by promoting responsible and safe mining practices as well as the better use of regional mineral resources.

The main types of spatial estimates are classified according to their purpose, such as assessing the spatial distribution of *in situ* attributes, for supporting short-term planning or controlling grades, and for classifying mineral resources and reserves (Deutsch et al., 2014). The evaluation of mineral resources from tailings deposition systems follows a similar methodology to that used for evaluating primary mineral deposits.

Tripodi et al. (2019) investigated the reclamation of two deactivated tailings deposits in Taltal, Chile, characterized by the presence of copper tailings and a mixture of mercury and gold. This study sought to quantify economically viable metals (gold, copper), heavy metal contaminants (mercury, arsenic, lead) and other substances (zinc, nickel, manganese) via the ordinary kriging technique for geostatistical modeling of these elements.

Nwaila et al. (2021) sought to demonstrate the feasibility of applying the Ordinary Kriging (OK) technique together with Sequential Gaussian Simulation (SGSIM) and the nonlinear geostatistical uniform conditioning technique for modeling the potential resources of a copper/cobalt tailings deposit. Wilson et al. (2021) investigated the resumption of mining in tailings dams in Taltal, Chile, with the goal of using the recovered products as inputs for the cement industry. The applied approach integrated the ordinary cokriging geostatistical modeling technique with a Discrete Event Simulation (DES) framework.

Soto et al. (2022) developed a routine to model and estimate the resources of the Haveri tailings dam in Finland. The Transitive Kriging (TK) and Ordinary Kriging (OK) methods were applied to estimate the quantities of gold, cobalt, copper and iron. Blannin et al. (2023) proposed a routine for modeling tailings dams in Davidschacht, Germany, where the elements with the highest concentrations were zinc, lead, copper and indium. In this study, the Universal Sequential Gaussian Simulation (USGS) approach associated with Minimum/Maximum Autocorrelation Factors (MAF) was applied to estimate the block models of the elements.

3. Mining Methods in Dams

The methods for recovering tailings deposits are determined from the characteristics of the deposits, the composition, the storage conditions, and the possibilities for transport, handling and end use of the tailings (Engels et al., 2004). Muir et al. (2005) reported that external factors such as topography and the presence of watercourses can predominate in the cost analyses of mining projects and the use of tailings.

There are three main methods for the recovery of tailings deposited in dams: hydraulic blasting, which commonly uses water jets with high-pressure cannons; dredging, whether hydraulic or mechanical; and mechanical excavating, in which equipment such as excavators, bulldozers and trucks are used. According to Alves (2015), each method has its own features and employability depending on the characteristics of the deposition, the area available for work and the alternatives for transportation and storage of the handled material.

Sousa (2020) noted that, in the design stage, the tailings recovery method must consider the *in-situ* density of the material and its homogeneity, the topography of the site, the presence of watercourses and weather conditions. These aspects can directly impact the investment costs of the project.

Muir et al. (2005) sought to categorize tailings recovery methods on the basis of their advantages and disadvantages to facilitate decision-making. The authors specifically highlighted the hydraulic blasting method as having the lowest operating cost among the methods analyzed. **Table 1** summarizes the methods highlighted by the authors.

Table 1. Comparison of the mining methods for dams.

	Advantages	Disadvantages
Hydraulic Blasting	1) Lower comparative operating cost; 2) Ability to control pulp density and flow, varying the number of operating guns and their opening; 3) Reduction in energy costs, with gravity flow to the pumping station; 4) Simple operating system, consisting of filters, pumps and ducts.	1) Low recovery in uneven terrain, which may require the use of mechanical methods for a complete recovery; 2) Requires the opening of an extensive trench by means of hydraulic blasting; 3) Significant interference during the rainy season in the dilution of the material; 4) More difficult to separate materials with economic value.
Dredging	1) There are no major changes in industrial water recirculation, and there is no need to eliminate flows external to the reservoir; 2) Allows operation in rainy periods, not suffering interference according to the season; 3) Minimizes turbidity and water consumption; 4) Best option in flooded areas; 5) Effective in areas with low support capacity for equipment traffic.	1) High cost of mobilizing and demobilizing the equipment; 2) Difficulty in recovering all the materials, especially ultrafine ones, due to equipment limitations; 3) Contracting by dredged volume; 4) Clogging of suction device by bottom vegetation; 5) Lower pulp density of the recovered material compared to other methods; 6) Higher total cost of recovery.
Excavators	1) Possibility of full recovery of the deposited tailings; 2) Possibility of separating materials with and without economic value before treatment in the plant.	1) Comparatively high cost of reclamation; 2) Need for a firm ground surface to support the traffic of earthmoving machines; 3) The cost of the operation would only be viable depending on the scale of production.

Source: Adapted from Muir et al. (2005).

Alves (2015) highlighted the importance of conducting technical-financial feasibility studies for the available methods to select the one most appropriate to the reality of each dam. In this context, the preponderance of the economic criteria must be balanced with the guarantee of geotechnical safety for mining operations.

4. Dredging

The Global Tailings Portal, created in January 2020, is a platform with a free and searchable database that includes information on 2056 tailings dams around the world. The portal was developed on the basis of responses published by the "Investor Mining and Tailings Safety Initiative" launched by the Church of England Pensions Board and the Council on Ethics of the Swedish National Pension Funds (Global Tailings Portal, 2024).

In an analysis of 1679 tailings dams performed by the portal, approximately 86% of the dams have a wet construction method. Thus, as most tailings basins are submerged or partially covered by water, dredgers are the equipment most adapted to operate in this type of environment.

Bray et al. (1997) elucidated the wide variety of dredging equipment and methods, many of which have evolved to meet specific needs, whereas others have demonstrated greater versatility. Some types of dredgers may not be able to perform certain dredging tasks or, in the best of cases, may operate with considerably reduced efficiency. The authors emphasized that, by meticulous designing dredging specifications, it is possible to minimize the diversity of equipment required or enhance the performance of specific equipment. Thus, properly understanding dredging methods is crucial during the design and planning phases of proposed activities. In addition, before the dredging equipment is chosen, it is useful to examine the physical mechanisms involved in the process, as there must be compatibility among the dredging equipment, the techniques used for excavation, the transport of the material and the management alternatives considered.

Engels et al. (2004) suggested that the dredging method should be used to excavate tailings underwater only if the dredgers are able to excavate the solid material at high depths and bring it to the surface. Granato (2005) indicated that dredgers can be classified as mechanical or hydraulic, depending on the movement of the material, and as centrifugal, pneumatic or aerial, in relation to the way in which the sediments are disaggregated. The author also emphasized that hydraulic dredging is ideal for removing fine sediments in liquid form that are slightly compacted. Mechanical dredging is ideal for coarser and more compacted sediments, in which a mechanical force is applied directly to dislodge and excavate the material. According to Alves (2015), the dredging method consists of dismantling, loading and transporting the material to the surface, similar to a continuous miner but in an aquatic environment.

When operating hydraulic dredgers, the cutter depth, excavation speed and dredge movement depend on operator experience. These parameters are directly influenced the soil characteristics, operational strategy, excavation depth, mud concentration, accuracy and yield prediction time (Wang et al., 2020).

Figure 1 shows the most common models of mechanical dredgers, including 1) an excavator dredger, in which the bucket is the shovel (dipper dredger) or backhoe (backhoe dredger) type; 2) a bucket ladder dredger; and 3) a grab dredger. **Figure 2** shows the most common models of hydraulic dredgers, including (a) a cutter suction dredger, (b) a trailing suction hopper dredger, and (c) a dustpan dredger.

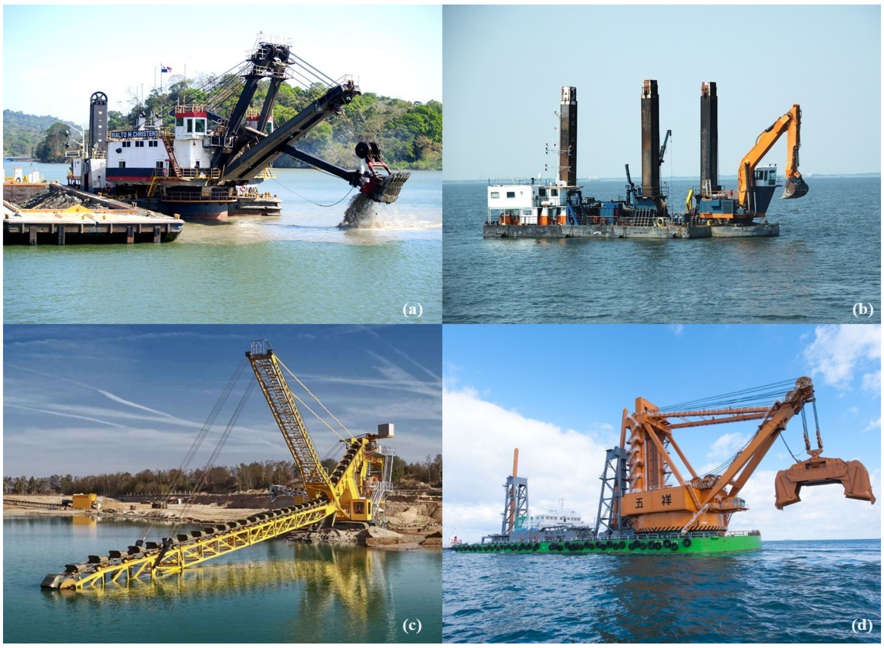

Figure 1. Mechanical dredgers: (a) dipper dredger, (b) backhoe dredger, (c) bucket ladder dredger and (d) grab dredger. Sources: (a) IADC (2024); (b) VLMS (2024a); (c) Rohr-Idreco (2024); (d) Kojimagumi (2024).

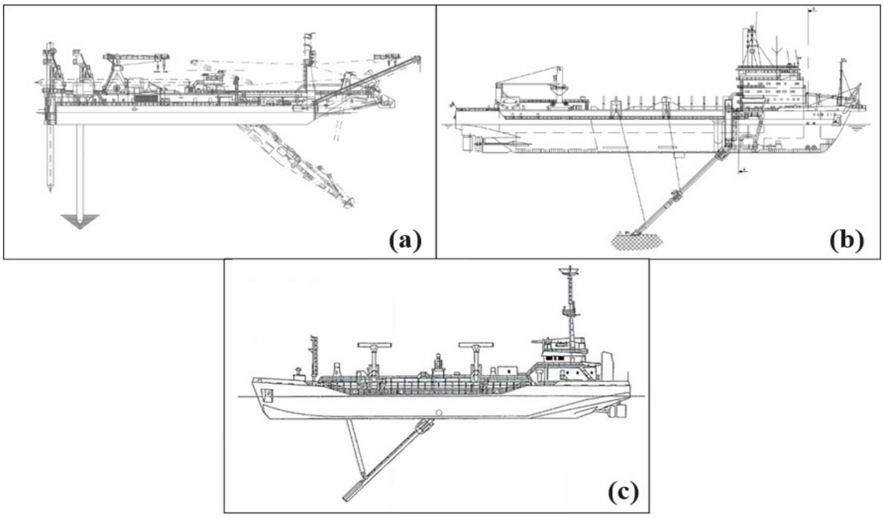

Figure 2. Hydraulic dredges: (a) cutter suction dredger, (b) trailing suction hopper dredger and (c) dustpan dredger. Sources: (a) VLMS (2024b); (b) Van Rhee (2022); (c) Bray et al. (1997).

In the literature, few scientific studies have focused on the dredging of tailings dams. However, some companies provide dredges and dredging services for this purpose and have engaged in several operations in tailings dams in different locations.

The Ranger Mine, operated by Rio Tinto and located in Australia, began dredging uranium tailings from a dam in 2015 via a cutter suction dredger (Hall Water & Tailings, 2024). At the Ernest Henry Mine, located in Australia, a cutter suction dredger was used to dredge copper and gold tailings from a dam (Fitton & Neumann, 2015). The Moura Mine, located in Australia, used a cutter suction dredger to recover coal tailings from the Moura 2C pit. These fine coal tailings were deposited at the bottom of the pit and needed to be removed for an underground mine project (Neumann Dredging, 2024).

The Gelado Dam, owned by the Vale Mining Company in Pará, used electric cutter suction dredger to recover iron tailings and contribute to more sustainable mining, reducing CO_2 emissions. The project provided for the recovery of 10 million tons of high-grade iron ore per year. In addition, within 10 years, the project is expected to prevent the emission of 484 thousand tons of CO_2 (IHC Mining, 2024).

The Las Lagunas Project, located in the Dominican Republic, installed a cutter suction dredger to recover gold and silver tailings from the Pueblo Viejo Dam. The dam is estimated to hold 5137 million tons of ore, with an average grade of 3.8 g/t of gold and 38.6 g/t of silver (Ellicott Dredges, 2014).

5. Sizing Dredgers, Pumps and Pipelines

Considering that the characteristics of dredged materials have already been analyzed and that a dredge model has already been preselected, to estimate the productive output, it is necessary to identify several factors. According to Bray et al. (1997), among these factors are the base productive unit (U_b), modified productive unit (U_m), modification factor (f_m), cycle factor (f_c), delay factor (f_d), operational factor (f_o), breakdown factor (f_b), instantaneous theoretical output (P_t), nominal uninterrupted output (P_{nom}), maximum potential output ($P_{\max}$) and output (P).

Equation (1) presents the function of the modified productive unit (U_m), and Equation (2) presents the average output (P) by considering the realistic factors of the operation.

$$U_m = f_m \cdot U_b \tag{1}$$

$$P = f_d \cdot f_o \cdot f_b \cdot P_{\max} \tag{2}$$

Cutter suction draggers are the most common dredging tools used in tailings dams. According to Vlasblom (2016), the design and sizing of cutter suction dredgers should be guided by estimated productivity, underwater excavation depth, type of excavated material, transport/pumping distance and access to the region of interest.

Bray et al. (1997) considered more relevant numerical information, such as 1) hp_d —the horsepower of the dredging pump; 2) hp_c —the horsepower of the cutter; 3) L—the length of the discharge pipeline, meters; 4) d —the average dredging depth, meters; 5) $d_{\max}$ —the maximum dredging depth for the dredger, meters; 6) z —the average thickness of the material to be dredger, meters; 7) a —the average advanced distance between side anchor movements, meters; 8) b —the width cut, meters; 9) p —the average distance advanced with each spud movement, meters; 10) t_a —the time taken to move the side anchor, hours; and 11) t_p —the time taken to advance on spuds, hours.

In addition, the D_{50} grain size must be known in the case of granular materials, and the N-value must be obtained through the Standard Penetration Test (SPT). The productivity of the dredger is dictated by the power capacity of its pump; however, it is necessary to know if the cutter will be able to cut the material. **Figure 3** shows the relationship between the power of the cutter and the competence of the material through the N-value obtained through the SPT.

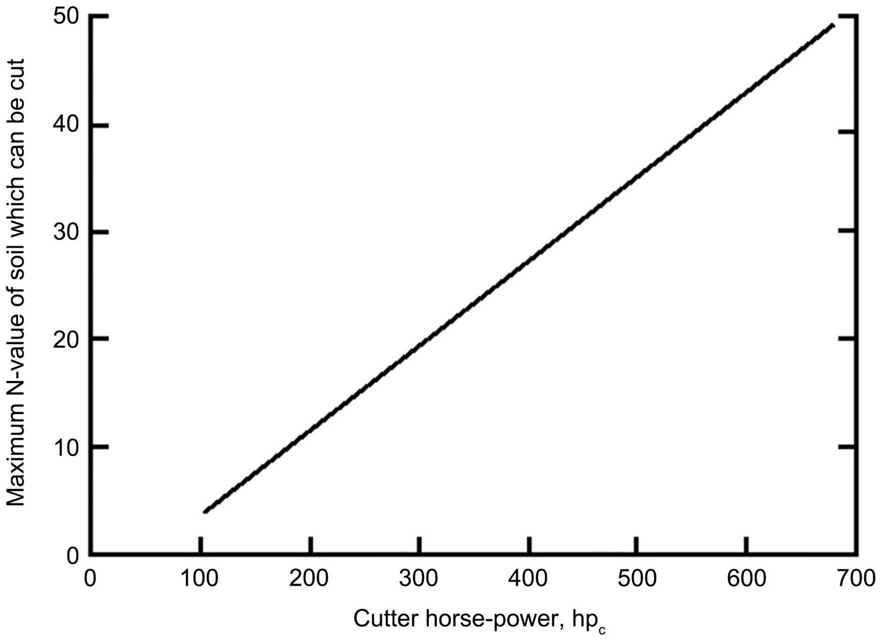

Figure 3. Cutter suction dredger: maximum N-value of soil which can be dredged with cutter horsepower, hp_c. Source: Bray et al. (1997).

Considering that the cutter has the production capacity to serve the pumps, it is necessary to determine whether the pumps will be sufficient to reach the discharge distance of interest for operation. **Figure 4** shows the pump power ratio, type of material and discharge distance to be completed.

To ensure that hp_c and hp_d are reached, the instantaneous theoretical output (P_t) can be defined. The modification factor (f_m) is obtained through the graph in **Figure 5** and can be applied to Equation (3) to calculate P_t.

$$P_t = f_m \cdot HP_d \tag{3}$$

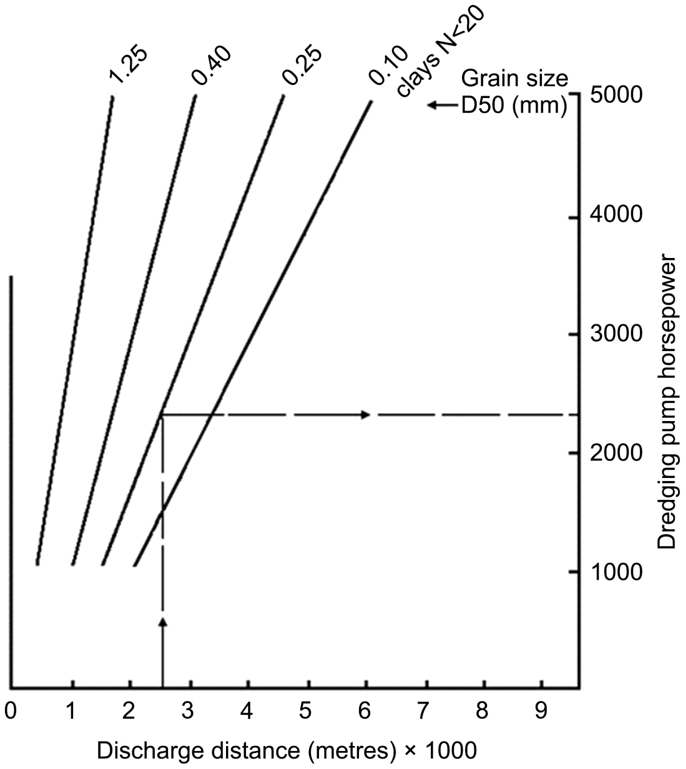

Figure 4. Cutter suction dredger: horsepower required on dredging pump for various discharge distances and soil characteristics. Source: Bray et al. (1997).

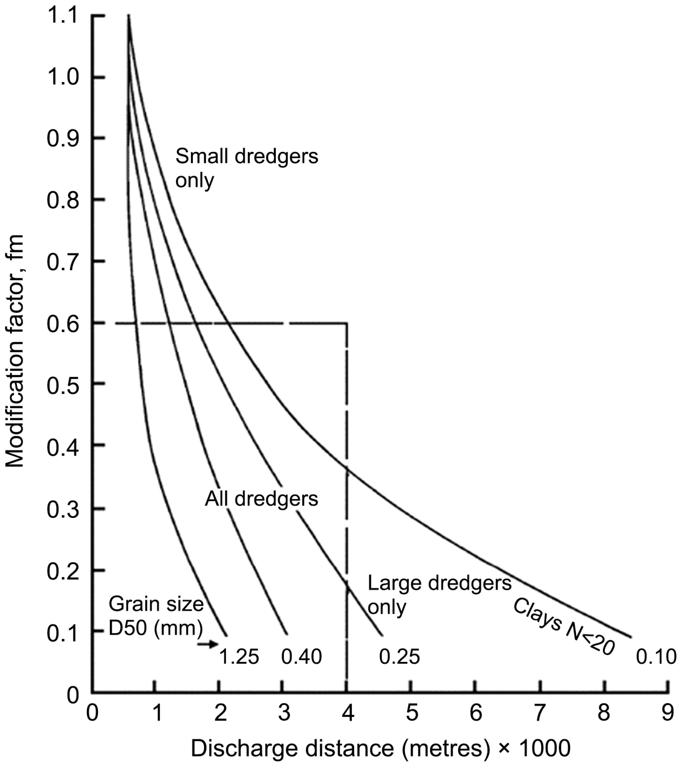

Figure 5. Cutter suction dredger: modification factor (f_m), for various discharge distances and soil characteristics. Source: Bray et al. (1997).

Examples of pumps used in dredging operations include centrifugal pumps, piston or plunger pumps, screw pumps, jet pumps and submersible pumps. The choice of pump type depends on the specific characteristics of the dredging site, the type of material to be dredged, the pumping distance and other environmental and operational factors.

For dredging operations, centrifugal pumps are most commonly used because of their ability to handle large volumes of fluids and their greater pumping capacity and suitability for solids transport. Several important factors must be analyzed when designing a pressurized slurry system with respect to preventing the sedimentation of solids in the pipeline, optimizing energy consumption, meeting operational requirements such as flow rate and solids mass, and minimizing the wear of the internal components in the pumps and piping.

Fundamentally, the installation specifications for a pump are a function of two important quantities: the flow to be pumped down (Q) and the head of the installation (H). In the case of slurries, the percentage of solids in the slurry required for dredging is also evaluated.

The first step when designing a pulp handling system is determining the actual transport speed, the "limit" speed (critical speed) and the diameter of the pipe. Chaves (2002) noted that the pumping speed of a heterogeneous slurry must meet two unequal and independent requirements: the speed must be fast enough to produce the turbulence necessary to keep the solids in suspension, and the speed should be as low as possible to reduce friction with the tube walls and reduce the pressure drop.

With homogeneous pulps, the speed can be as low as convenient. From an operational or economic point of view, the ideal pumping speed must be determined experimentally. In heterogeneous pulps, the bed is formed in a fully turbulent regime because of the characteristics of the solids. This deposition velocity ("threshold" flow velocity) is thus the critical flow velocity. For pressurized lines inside industrial facilities, the modified Durand equation (1952) has been adopted to define the flow limit velocity, as shown in Equation (4).

$$V_L = \left[F_L \cdot \sqrt{2 \cdot g \cdot D \cdot \left[\left(\frac{\rho}{\rho_w} - 1 \right) \right]} \right] \cdot \sqrt{\frac{c_m}{0.45}} \tag{4}$$

where:

- V_L: Durand's limiting solids setting velocity in the pipe [m/s];
- F_L: Durand's parameter for limiting the settling velocity in a pipe [dimensionless];
- g: Gravitational acceleration [m/s^2];
- D: Inside diameter of the pipe [m];
- ρ: Density of solids [kg/m^3];
- ρ_w: Density of liquid, usually water [kg/m^3];
- C_w: Concentration of solids in the slurry, by weight [%].

To use this equation, it should be noted that the percentage of solids must be less than or equal to 45%. For cases in which the percentage of solids is greater than 45%, the last term of the equation should not be considered. The FL factor can be obtained through the graphs shown in **Figure 6** and **Figure 7** as a function of the particle diameter and volumetric concentration of solids (C_v).

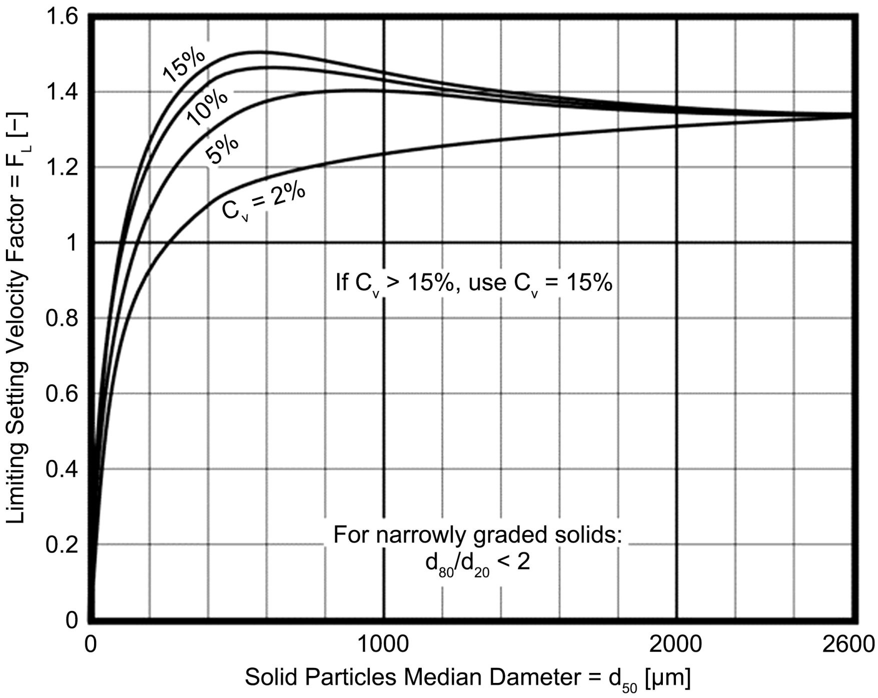

Figure 6. Durand's limiting settling Velocity graph. Source: Weir (2002).

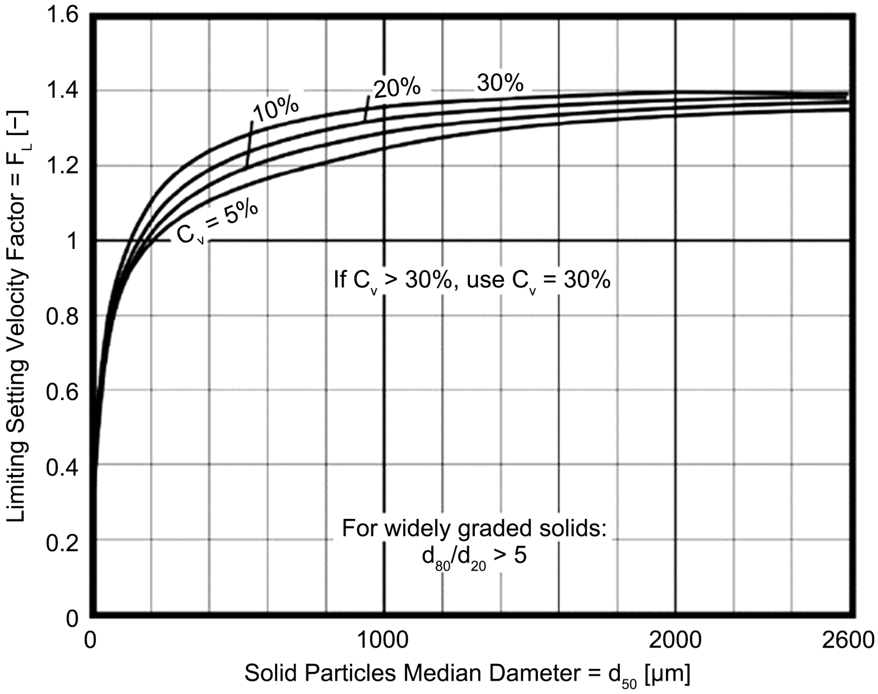

Figure 7. Modified limiting settling Velocity graph. Source: Weir (2002).

The determination of the average velocity of flow in a pipe (V) follows the continuity equation expressed by Equation (5), where the flow rate (Q), in m^3/s, is known. Knowing the area (A), in m^2, substituting the terms and reorganizing the equation, V, in m/s, can then be calculated according to Equation (6).

$$Q = V \cdot A \tag{5}$$

$$V = \frac{4 \cdot Q}{\pi \cdot D^2} \tag{6}$$

The calculation of the diameter (D), in m, of the pipe is based on the relationship in which V_t is greater than V_L, establishing the theoretical diameters for the pipe and aiming to operate without the risk of sedimentation and obstructions. When choosing the actual pipe diameter, one should always choose a diameter smaller than that theoretically calculated. This decision ensures that the transport velocity of the pulp is greater than the sedimentation velocity of the particles.

After the diameter of the pulp transport pipe is defined, the subsequent step involves determining the head loss of the system. The unit head loss value can be calculated from the Darcy-Weisbach equation, proposed in 1845 (Equation (7)).

$$H_f = f \cdot \frac{L}{D} \cdot \frac{V^2}{2 \cdot g} \tag{7}$$

where:

- H_f : Friction head loss in pipe [m];
- f : Darcy's pipe friction factor [dimensionless];
- L : Length of pipe [m];
- V : Average velocity of flow in the pipe [m/s];
- D : Inside diameter of the pipe [m];
- g : Gravitational acceleration [m/s].

6. Conclusion

This review provides a comprehensive overview of the main considerations related to mining tailings dams. This activity stands out as a strategic and promising alternative for mining companies, as it aims to recover tailings with high metallic contents that were previously unprocessed.

Geostatistical modeling is still in its infancy in tailings dams, but it is already possible to see recent publications that use kriging as a tool for estimating reserves, presenting itself as a viable tool for this purpose. In addition, probabilistic simulations have also gained ground as alternatives for quantifying reserves.

Although mining methods such as mechanical excavation, hydraulic blasting and dredging have been used for other purposes, studies that address the application of these methods in the mining of tailings dams are lacking. The integration of advanced technologies, precise sizing methods and specific characteristics of the materials to be manipulated are essential for the success of these operations.

Therefore, mining tailings dams not only represents a significant economic opportunity but also reinforces environmental responsibility and encourages innovation in the sector. The implementation of sustainable practices and compliance with environmental regulations emerge as crucial factors in the search for more responsible and ecologically sustainable mining operations, configuring alignment with the concepts practiced and a circular economy.

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Conflicts of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship and/or publication of this paper.

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