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Review

In-Pit Disposal of Mine Tailings for a Sustainable Mine Closure: A Responsible Alternative to Develop Long-Term Green Mining Solutions

Carlos Cacciuttolo [1,*] and Edison Atencio [2,3]

1 Civil Works and Geology Department, Catholic University of Temuco, Temuco 4780000, Chile
2 School of Civil Engineering, Pontificia Universidad Católica de Valparaíso, Av. Brasil 2147, Valparaíso 2340000, Chile
3 Department of Management, Economics, and Industrial Engineering, Politecnico di Milano, Via Lambruschini 4b, Bovisa, 20156 Milan, Italy
* Correspondence: ccacciuttolo@uct.cl or carlos.cacciuttolo@gmail.com

Abstract: In the next decades many of the old tailings storage facilities (TSFs) could be re-processed if one considers the prices of metals, new uses of metals which today are not valuable, and the application of new, more efficient metallurgical technologies. In this context, in-pit disposal of mine tailings (IPDMT) is an attractive alternative to be used as part of responsible mine closure: mines could reprocess the mine tailings and place them in an open pit as part of sustainable mine closure. This article explores a little-explored tailings disposal technique that has the potential to be considered as an environmentally friendly solution, returning mine tailings to their place of origin and providing long-term stability under a climate change scenario. This article presents the main features, benefits, and potential drawbacks of IPDMT, with an emphasis on: (i) a description of the main advantages and disadvantages of application; and design issues related to (ii) IPDMT physical stability (pit slope stability, tailings transport, placement systems); (iii) IPDMT hydrological stability (water management, seepage control, hydrogeological monitoring,); and (iv) IPDMT geochemical stability (geochemical characterization, acid rock drainage control, covers). The novelty of this article is the proposal to change the status quo of traditional management of mine tailings to a new paradigm where the technique of in-pit disposal of mine tailings can be considered a green mining solution for mine closure. Finally, some successful cases around the world that involved the implementation of this technique are presented.

Keywords: mine tailings; open-pit mines; in-pit tailings disposal; mine closure; environmental impact reduction; acid mine drainage control; sustainability

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1. Introduction

1.1. Open-Pit Mines and Mine Tailings Management

Mineral exploitation using the open-pit mining method is an attractive alternative to the underground mining method when the deposit has relatively superficial mineral veins [1] (Figure 1). The open-pit mining method requires not only removing ore, but also waste rock, which has low amounts of the beneficiary metal [2]. An average ratio between ore-bearing rocks and waste rocks can vary between 1:2 and 1:3, depending on the depth of the ore vein and the age of the mining operation (early, middle, or late stage) [3,4]. The ore rocks are generally transported by mining trucks to the crushing stages, to later be driven by conveyor belts to the mineral concentration metallurgical plant, in the case of sulphide minerals [5].

Large amounts of waste rock are also transported by mining trucks, but these are driven to special areas called mine waste deposits, where they are conditioned to avoid the generation of acid rock drainage [6,7]. As the open pit deepens, the operation becomes more expensive due to the enormous amount of rock that needs to be removed, considering the transport distances that mining trucks must cover [8]. It is for this reason that some mining projects such as Codelco's Chuquicamata copper mine in Chile are changing from an open-pit mining method to an underground mining method, in order to make operations more cost-effective [1].

Figure 1. An open-pit mine—a free place to store mine tailings.

Another type of sterile material or mining waste generated in the metallurgical treatment of concentration of sulphide minerals is mine tailings. Usually, the mine tailings are transported and deposited in a site near the concentrator plant where a dam is built and stored during the useful life of the mine [9]. Neither waste rock nor mine tailings may be deposited in the open-pit mine during operation, so as not to interfere with drilling, blasting, and rock hauling [10]. However, once the mineral exploitation activities in the open pit end, the open pit becomes an attractive site to store mineral matter considered as mining waste at its place of origin [11].

Some of the largest open pit copper mines in the world are Chuquicamata Mine in Codelco, Chile and Escondida Mine in BHP Billiton, Chile (Figure 2). The main dimensions of the open pits are shown in Table 1.

Table 1. The three largest open-pit copper mines in the world.

Open Pit Name	Mine Name	Company Name	Country	Open Pit Depth (m)	Open Pit Length (km)	Open Pit Width (km)
Chuquicamata	Chuquicamata	Codelco	Chile	1000	5.0	3.0
Main Escondida	Escondida	BHP Billiton	Chile	645	3.9	2.7
Escondida Norte	Escondida	BHP Billiton	Chile	525	2.5	2.2

Historically, open pits have been left open until mine closure (see Figure 2), unless, due to conditions of lack of space in the mining project for mine waste rock, it is necessary to store them in the open pit. In some cases, open pits must be filled in to avoid unwanted effects due to the generation of acid rock drainage that can occur at the bottom of the open pit or on the side walls formed by the slopes. In addition, in the case of backfilling the open pit with mine waste, it is necessary to carry out a study that indicates that the backfill materials are non-potential acid generators (NPAG) [3,7].

Storing mine tailings in an open pit of the mine could reduce the ecological footprint of the mining project, considering that surface tailings deposits are the facilities with the largest area of land use, generating a great socioenvironmental impact [8]. In addition, the in-pit disposal of mine tailings is an efficient use of space, and reduces closure and remediation costs, since the construction of dams with heights of 100 m, site grading fills, and civil works such as spillways and contour channels is avoided [10].

Figure 2. Aerial views of (**a**) Escondida Mine Main Open Pit; (**b**) Chuquicamata Mine Open Pit.

Disposal of mine tailings into open pits can be used when mining has ceased and is therefore most viable in a multi-pit operation or where abandoned pits are nearby [12]. Even then, future resources must not be compromised. When to cease the operation of an open-pit mine is not always clear. This is because the mineral-rich body can be located laterally or vertically. Mining or processing costs may be too expensive at today's prices. Extensions to the ore body could be mined in the future by underground shafts or declines from the pit floor. Once the pit has been filled with tailings, further mining is, in essence, ruled out [2,13].

Considering the potential for acid mine drainage (AMD) generation in mine tailings compared to mine waste rock, the fine grain size and high moisture content result in low permeability for oxygen flux. This very low permeability in mine tailings does not allow for significant advective or convective transport of oxygen gas. In the case of applying the in-pit disposal of mine tailings, gaseous diffusion is the most important oxygen transport mechanism, which, to a lesser extent, could affect the generation of acid mine drainage (AMD) [14].

1.2. Re-Processing of Old Mine Tailings Deposits

Many mines around the world are evaluating the reprocessing of their old mine tailings [15,16]. Mining tailings processed with old metallurgical technologies still have attractive grades of valuable metals, which implies a lower production cost [17–19]. Another reason to reprocess old mine tailings is to obtain critical metals of emerging interest, such as cobalt, vanadium, gallium, germanium, and rare earth elements (REEs) [20]. There is a significant demand for these critical metals, mainly by the electronics and renewable energy industries [21].

In addition, reprocessing old mine tailings offers the opportunity to apply circular economy principles and carry out responsible and sustainable closure of mine tailings, for example, depositing them in open-pit mines, their place of origin [22–24] (Figure 3).

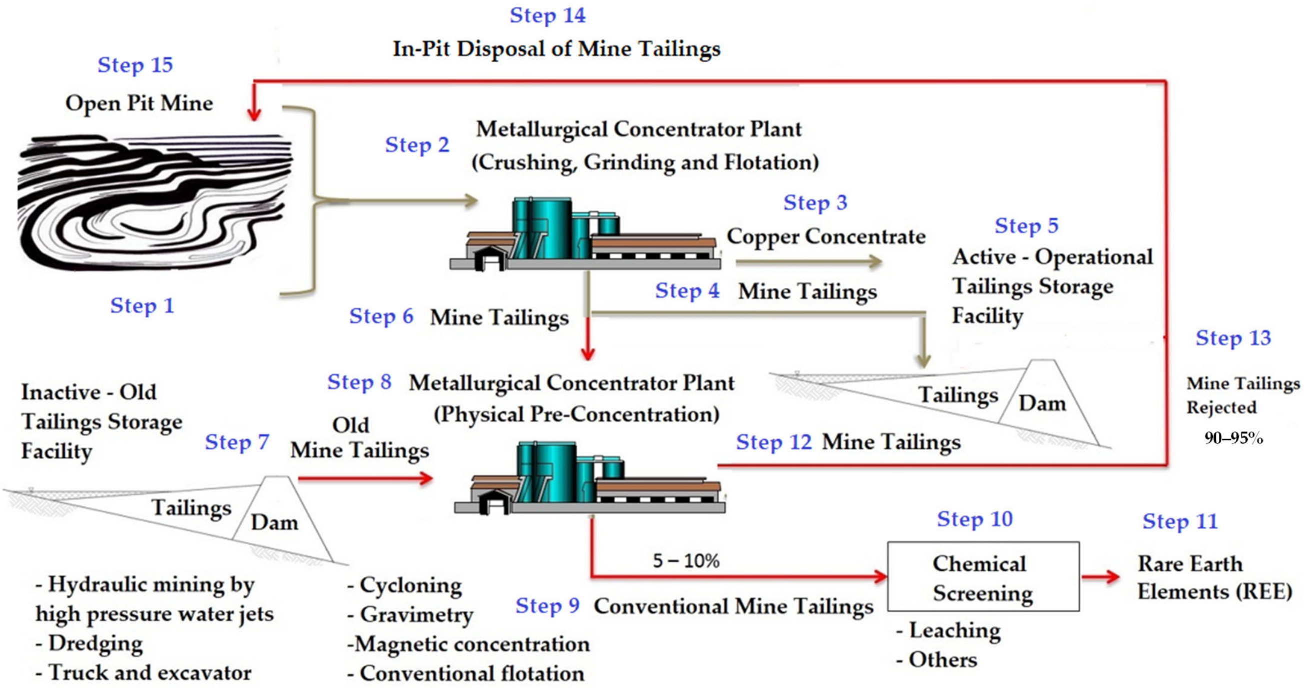

Figure 3. Conceptual process diagram of mine tailings reprocessing and in-pit disposal of mine tailings.

In-pit mine tailings disposal is particularly attractive if the old tailings storage facilities at a closed mine can be reprocessed and deposited into a worked-out open pit [25]. Typically, mining companies plan to extract the tailings from old tailings storage facilities (TSFs) to reprocess them using mechanical equipment consisting of floating platforms that have dredging pumps; it is also feasible to use hydraulic mining monitors (high-pressure water jets; see Figure 4). In this way, the old dry tailings are transformed into pulp-type wet tailings and, later, transported hydraulically in pipelines to the metallurgical processing plant [26–28]. Once the old tailings are subjected to concentration stages in flotation cells, the valuable metals are extracted, and new tailings are generated. These newly generated tailings can be transported to the open-pit mine and stored there [10,11].

This is how mining tailings can be transformed from a residue into a resource, which allows mining in some cases to remedy past bad experiences of old tailings deposits [29]. This could eliminate litigation between communities and mining companies due to socioenvironmental problems in the management of old tailings deposits, allowing a more sustainable relationship between all stakeholders [30–33].

1.3. Aim of the Article

The article presents the in-pit disposal of mine tailings as a post-mining operation technique, which is most practical in a multi-pit setup or when abandoned pits are available nearby. However, it is important to ensure that this activity does not compromise future resource extraction. In addition, the article outlines the key features, benefits, and considerations of In-Pit Disposal of Mine Tailings (IPDMT), with a focus on the following aspects: (i) describing the advantages and disadvantages of its application; (ii) addressing design issues for IPDMT physical stability, (iii) discussing IPDMT hydrological stability, and (iv) exploring IPDMT geochemical stability. Finally, the article presents some real-world examples of successful IPDMT implementation around the globe, showing that in-pit disposal of mine tailings is a technique for sustainable mine closure, developing a long-term environmentally friendly mining solution.

Figure 4. Mine tailings reprocessing at Los Colihues TSF using high-pressure water jets, El Teniente Copper Mine, Chile.

2. Concept of In-Pit Disposal of Mine Tailings

The technique of in-pit disposal of mine tailings (Figure 4) is feasible to apply when there is no mineral resource exploitation activity in the open pit. This can occur when there are multiple open pits that must be excavated in separate sectors. This tailings storage technique is attractive when the operations for the exploitation of mineral resources in the open pits have ended, leaving a free space to deposit the mine tailings [3,34,35].

In-pit disposal of mine tailings (IPDMT) means the safe and controlled depositing of mine tailings within the open pit, where the density of the deposited tailings increases due to consolidation and, at the same time, the supernatant water pond produced by the sedimentation of tailings is handled by means of pumping systems. (Figure 5).

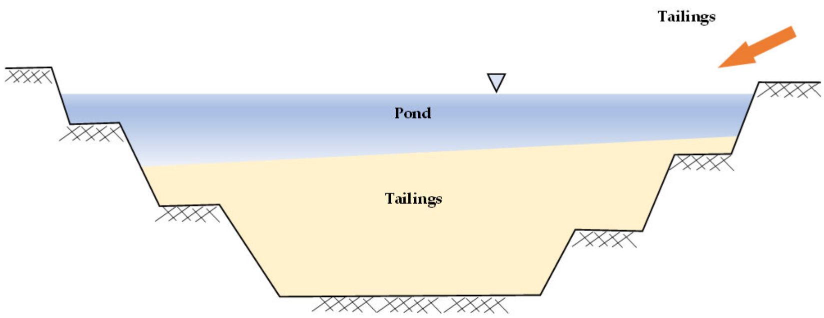

Figure 5. Schematic of in-pit disposal of mine tailings.

The following key issues are relevant from a regulatory perspective with respect to IPDMT:

- Presence of any mineralization at the base of the pit that may be attractive for exploitation.
- Presence of groundwater resources, and the minimization of groundwater contamination.
- Stability of pit walls.
- Tailings characteristics.
- Operational aspects.
- The need for the final tailings surface to be either 5 m above or 5 m below the natural water.

Usually, the transport of mining tailings is in the form of pulp, hydraulically transported through pipes [36]. Once the tailings reach the open-pit mine, a series of discharge points (spigots) are defined on the perimeter of the open pit. Tailings are discharged in such a way as to allow the formation of a tailings beach near the spigots and the generation of a process water pond far from the discharge points [37].

The process water from the supernatant process water pond can be managed with floating hydraulic pumps in such a way as to keep the volume controlled and be able to reuse the water in the metallurgical process of the concentrator plant [38,39].

Figures 6–8 present the layout of a typical mining tailings deposit scheme in an open-pit mine, where the formation of a tailings beach and supernatant process water pond are indicated.

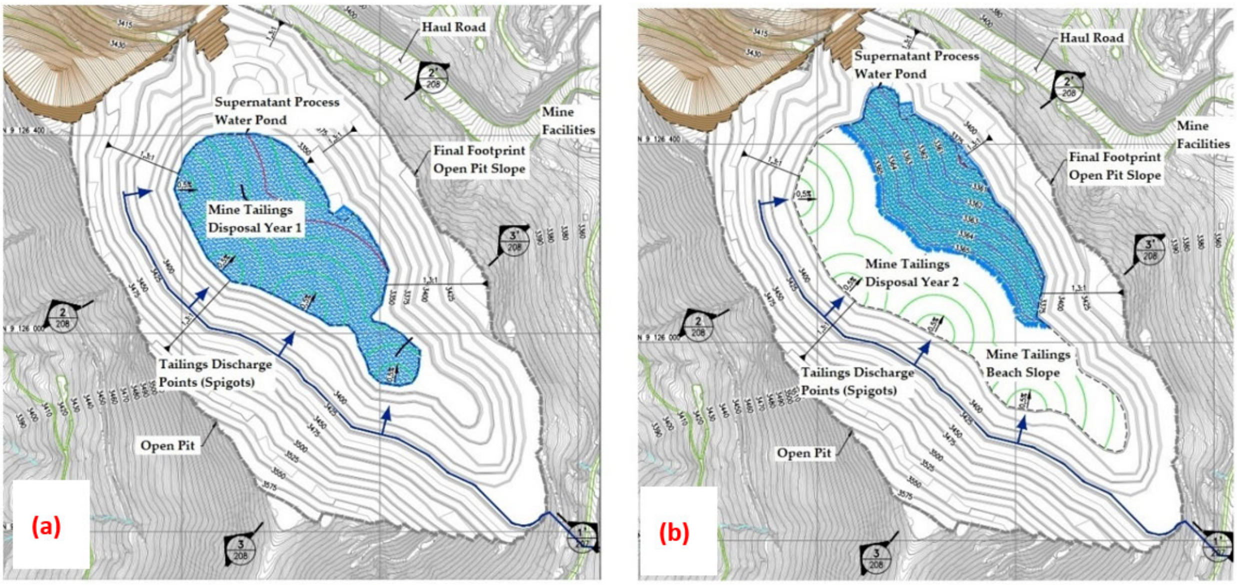

Figure 6. In-pit mine tailings deposition scheme 1 of 4—layout view: (**a**) IPDMT year 1; (**b**) IPDMT year 2.

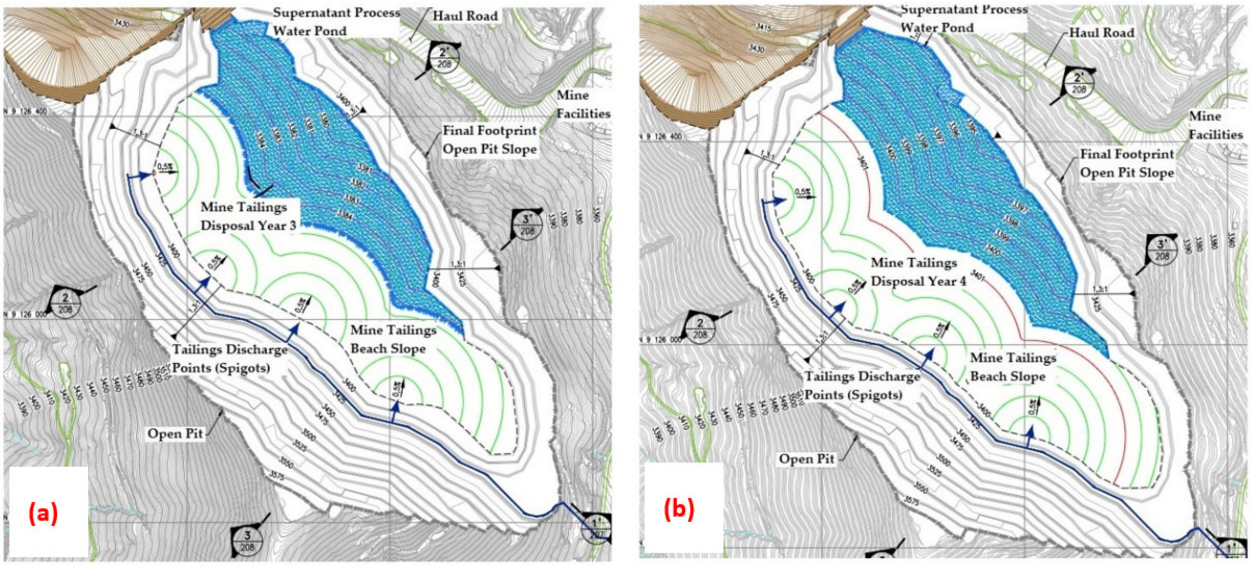

Figure 7. In-pit mine tailings deposition scheme 2 of 4—layout view: (**a**) IPDMT year 3; (**b**) IPDMT year 4.

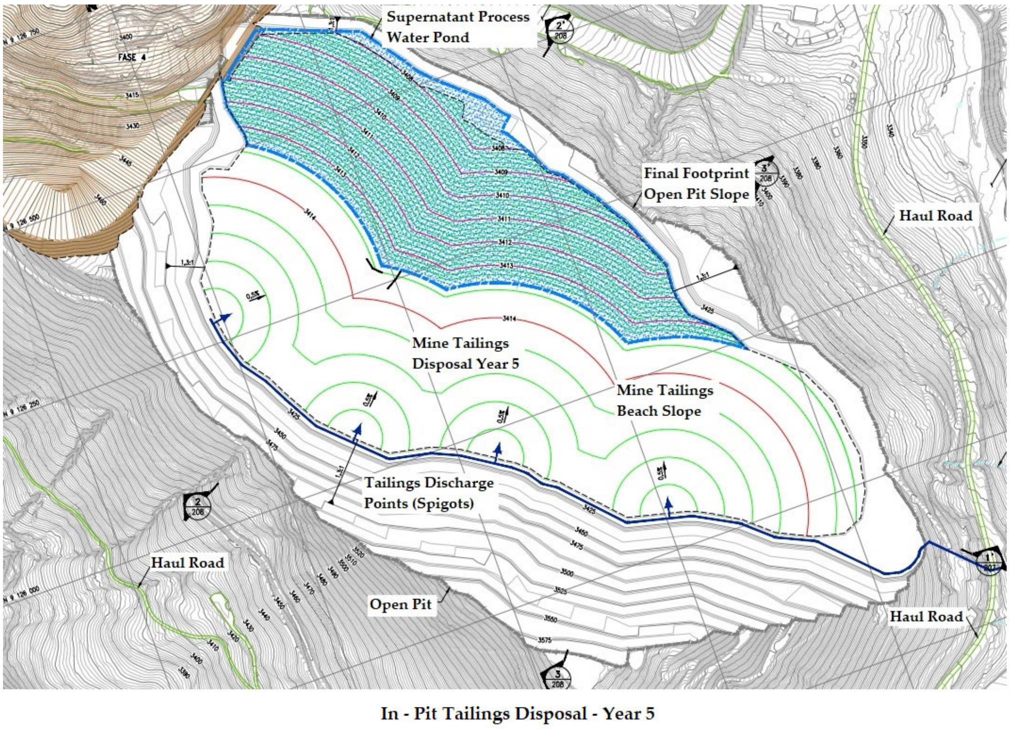

Figure 8. In-pit mine tailings deposition scheme 3 of 4—layout view: IPDMT year 5.

The study of mining tailings filling in the open pit must consider some key parameters such as the mining tailings production rate in metric tonnes per day (mtpd), the density of mining tailings, and open pit topography, among others. Water management within the open pit must also consider the presence of snow and rain. To this end, a filling plan must be designed such that it allows for a freeboard at all times and avoids any possibility of overflow of mine tailings or water that has come into contact with the tailings [38].

Figure 9 presents a typical cross section of an IPDMT, where it is possible to observe the level filling of mine tailings for every year, the tailings beach slope, and the supernatant process water pond location.

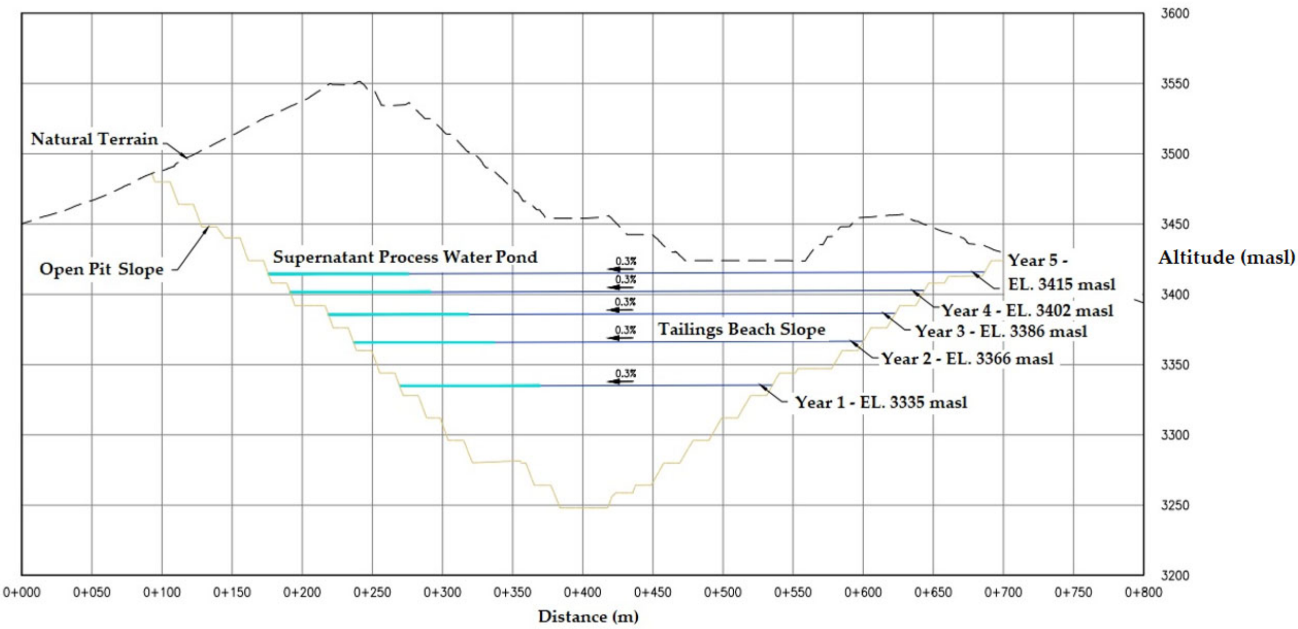

Figure 9. In-pit mine tailings deposition scheme 4 of 4—typical cross section, 2–2′.

3. Design to Ensure the Physical Stability of In-Pit Tailings Storage Facilities

3.1. Pit Slope Stability

During the development of an open-pit mine, responsible management of the slopes must be carried out in such a way that the risks of instability of the walls are minimized at all times. Slope stability will depend on carrying out geological, geotechnical, and hydrogeological studies, as well as understanding the danger in case of not implementing designs with conservative and safe criteria. All this must be complemented with the application of the most advanced slope monitoring technology in real time, whether using drones, satellite images and radar. In this way, efficient, economical, and safe operation will be ensured [7,10].

It is necessary to provide vehicle and machinery access to the open pit, to allow installation and maintenance of tailings discharge piping systems and water recovery piping systems and hydraulic pumps. Access ramps used by mining trucks must be available. It must be verified that ramps, banks, and berms are in optimal condition to avoid any collapse or rockfall. Geotechnical slope monitoring technologies, with the support of radar and drones, should be common practice in this type of project, especially considering large open pits [4,8].

3.2. Tailings Process: Dewatering, Transport, and Distribution

The successful IPDMT must consider the processes of sedimentation and consolidation of the mining tailings, producing the dehydration of the material over time, which will form a supernatant pond with processed water. It is important that the tailings release water, but it is also key that this water can be withdrawn and recovered, for example with the use of floating pumps in rafts. Dehydrating the tailings will allow the implementation, for example, of covers and thus a progressive mining closure [40].

The IPDMT design requires considering the water table inside the open pit and implementing the necessary drainage systems. In addition, it is important to ensure adequate access roads and ramps to the different levels of the open pit, so that vehicles carrying personnel can enter for the installation/removal of tailings pipes, inspection of ponds and water-pumping equipment, and installation/removal of water pipes. The tailings deposit scheme requires studying the location of the supernatant process water pond, always leaving the access ramps for vehicles operational. This is different from a conventional TSF, where there is a water recovery tower or the position of the floating rafts with hydraulic pumps is fixed [36].

3.3. Raising Rate and Consolidation of Tailings

The rate of filling with mine tailings in the open pit can be quite fast, particularly at the base of the open pit, where the surface area is smaller. Then the deeper layers of deposited tailings will have high consolidation rates, while the outermost layers will have lower densification and low levels of consolidation. It is feasible in some cases to implement drainage systems in the open pit to support the tailings consolidation process, capturing the water expelled from the mine tailings [41].

The consolidation process of mine tailings deposited in an open pit is likely to be faster compared to tailings deposited from a conventional surface tailings storage facility (TSF), due to the confinement provided by the side walls of the open pit formed by the slopes. The consolidation can last for years considering the operating times of a mining operation, and therefore, over time, differential settlement can manifest on the tailings surface, which will end once high levels of consolidation are obtained [42].

In the event of groundwater flow in the open pit, if the water is extracted below the water table, the open pit will be refilled with groundwater if the hydraulic pumps are not operational. If the deposit of mine tailings in the open pit is performed under these conditions, the tailings will have low deposit densities and there will be a low level of consolidation. This could cause certain problems, for example, with carrying out certain tasks inside the open pit, such as the installation of tailings and water pipes, as well as the progressive closure of the tailings surface with the installation of covers.

Because of the continuing rise of water from consolidation, the surfaces will be slow drying and will have low strength. Access to the tailings will be difficult for mine closure activities such as the spreading of cover materials, completion of pit filling, or revegetation [43].

Considering the production levels of tailings from medium- and large-scale mining companies, there can be mine tailings deposition rates of the order of 100,000 mtpd, which results in high levels of mine tailings consolidation. In these tailings deposits, important vertical settlements are recorded throughout the operation stage, including the application of cover materials to avoid the emission of particulate matter or to carry out a progressive closure, which generates settlements. Thus, it is important to carry out these activities to take into account the vertical settlements of the deposited tailings, in such a way as to eliminate risk of accidents and ensure safe conditions for workers.

4. Design to Ensure the Hydrological Stability of In-Pit Tailings Storage Facilities

4.1. Surface Water Management

Each application of the IPDMT technique requires a bespoke design to ensure physical and hydrological stability, especially controlling the flows of groundwater and surface water from aquifers and rainfall, respectively. In this sense, the main water management systems required are:

- A channel system to capture and divert rainwater without contact with the mine tailings and prevent its entry into the open pit. For example, channels can be dug into the ground and lined with geoweb/concrete, or one can use precast fabrics with concrete [40].
- Provide a groundwater management system through drainage ditches on the walls and bottom of the open pit. In addition, this system must be connected to a pumping system in permanent operation, which removes underground water flows and sends them to metallurgical plants for the reuse or irrigation of mining roads to avoid the emission of particulate matter [44].
- Both surface water and groundwater management systems must be managed in such a way that they do not affect the chemical quality of the water in the hydrographic basin where the open pit is located. If the water collected around the open pit is treated and meets local water quality standards, these flows can be discharged into the environment. If this is not the case, the collected water must be reused in the metallurgical process, generating a closed water management circuit and avoiding any type of environmental impact or contamination. In addition, it is necessary to implement a series of monitoring wells in the perimeter of the open pit, in order to periodically monitor the chemical quality of groundwater [31].

4.2. Water Table Monitoring and Supernatant Process Water Pond Control

In the implementation of the IPDMT technique, as in conventional TSF tailings deposits, it is important to take into account the potential environmental impacts to be generated by seepage (Figure 10). Seepage flows can have two points of origin: (i) from the supernatant process water pond or (ii) from the deposited tailings that are affected by consolidation. The key parameter to consider in these cases is permeability, which will have anisotropic characteristics, which means there will be great variability in space and over time. Over time, the tailings will densify and consolidate, which will cause a reduction in permeability [38,39].

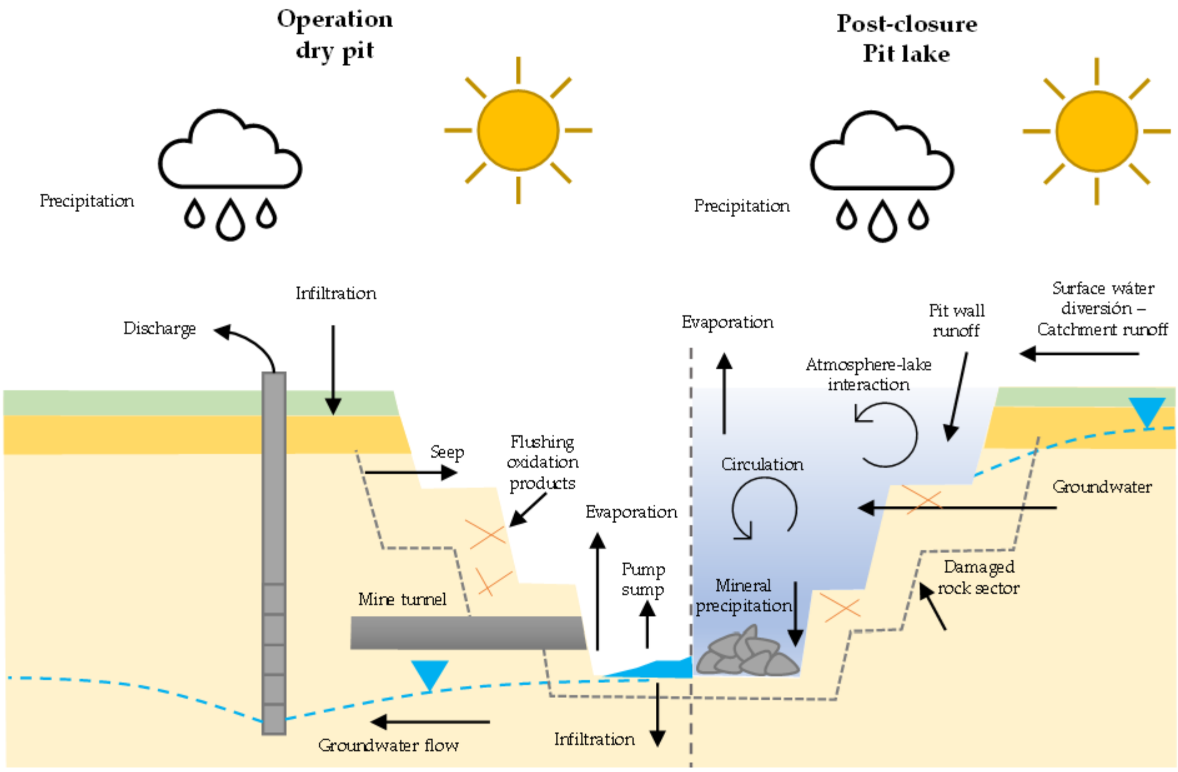

Figure 10. Typical groundwater tables in an open-pit mine.

There are two types of open pits that should be taken in consideration, those:

- Wholly above the groundwater table;
- In contact with the groundwater table.

Groundwater management within and around the open pit will require a permanent monitoring program, and thus provide an adequate quantity and quality of water in the watershed where the open pit lies. This is necessary in order not to negatively impact neighbouring communities and to comply with regulations imposed by local authorities [36].

4.3. Hydrogeological Surveys and Seepage Control

The permanent monitoring of groundwater must be carried out in conjunction with the application of computational models that represent: (i) the behaviour of filling the open pit with mine tailings, (ii) the hydrogeology flow network considering the amount of water, and (iii) the metal content, pH, hydraulic conductivity, etc., of hydrogeology considering water quality [39] (Figure 11). The following key aspects need to be considered:

- A leak collection system must be installed both in the bottom and on the walls of the open pit. Chimney-type drains can be provided on the walls, as well as carpet or herringbone-type drains at the bottom of the open pit.
- It is necessary to install a network of monitoring wells on the perimeter of the open pit and take periodic samples to verify that water quality standards are met. In particular, the situation of the IPDMT technique should be studied when there is and is not a rainy and snowy season in the sector. Greater care must be taken in case of depositing gold mining tailings with cyanide residues and uranium mining tailings with high levels of radiation and radon toxic gas.
- Continuous monitoring of the groundwater quality in a network of monitoring wells. Additional monitoring wells (at greater distance from IPDMT) will be installed to allow validation of modelling predictions.

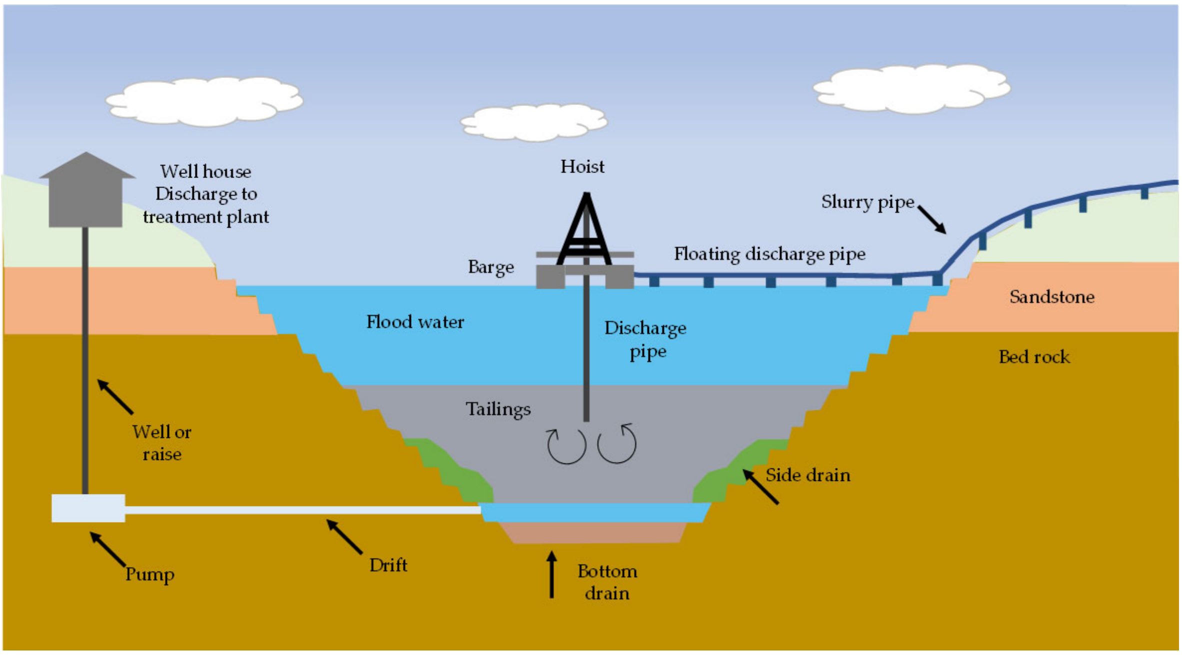

Figure 11. In-pit disposal of mine tailings—water management and monitoring model.

5. Design to Ensure the Geochemical Stability of In-Pit Tailings Storage Facilities

5.1. Acid Mine Drainage Issues

Acid mine drainage (AMD) is a serious problem worldwide, where some mining project facilities such as (i) mine waste deposits, (ii) tailings deposits, (iii) underground mine entrance, (iv) open pits, etc., generate effluents with low pH values close to 1 or 2, with the consequent release of heavy metals such as Pb, As, Cd, Fe, Cu, etc. The AMD has a severe environmental impact on the hydrology of a watershed, and damages people, flora, and fauna. All the aforementioned mining facilities, having a mineralogy that contains certain levels of pyrite sulphide minerals when in contact with environmental conditions of oxidation and water considering rainfall, can be a potential generator of acid mine drainage (AMD). It is for this reason that, in every mining project, the mineralogical and geochemical characterization of the different mining facilities must be studied from the beginning so that measures can be implemented to reduce the negative impacts of AMD [45].

The AMD in tailings deposits can be controlled by considering different forms of storage. The main objective of avoiding the generation of acid mine drainage (AMD) is to reduce contact with oxygen and water in the mine tailings. This is how conventional depositing on the surface exposes mine tailings to be potential generators of acid mine drainage (AMD), while other techniques reduce the generation of AMD from mine tailings, such as underwater deposition (in lakes or at the bottom of the sea) in open-pit or underground mines (within the stopes of an underground mine) [46].

In the case of the deposit of tailings at the bottom of the sea, this has been prohibited in several countries around the world, due to the high risk of contamination of marine ecosystems. There are several historical cases of underwater depositing of tailings in the sea where the environmental damage has been considerable. The advantage of this technique is that the mine tailings are stored in reducing conditions without oxidation, which considerably reduces the risks of generating AMD. Some examples are (i) Chañaral Bay, Chile, (ii) Ite Bay, Peru, and (iii) Portman Bay, Spain. The environmental impacts on flora and fauna have been reflected in alterations of the trophic chain. Therefore, the feasibility of implementing the technique of depositing mining tailings in the sea will depend on the environmental impact assessment that can be generated, the approval of the community, and the local authorities [47].

In the case of depositing mining tailings in an open pit, it is possible to reduce the contact of the tailings with oxygen and water, considering the walls and bottom of the open pit, which generates a kind of encapsulation of the mine tailings. In addition, considering the high rates of consolidation of the tailings inside the open pit, it is possible to apply coverage techniques through progressive closure activities of the facility, which allows for the application of environmental remediation techniques, for example, through phytostabilization of the surface of the mine tailings [19].

5.2. Prevention of Acid Rock Drainage

To avoid the environmental impacts and high remediation costs of AMD, prevention is key and must be developed in every mining project. The most common AMD prevention activities are the following: (i) elimination of pyrite contents, (ii) reduction of contact with oxygen, and (iii) water management. Considering recent experiences worldwide, it is possible to remove the pyrite in mine tailings prior to deposition, which is effective at reducing the generation of AMD. A second alternative consists of storing mine tailings with the potential to generate acid mine drainage (PAG) in a reducing or anoxic environment, avoiding metal leaching, sulphide reaction, and heavy metal migration. An AMD control activity in mining tailings storage facilities can be placing an effective and durable barrier to prevent contact with oxygen, such as wet covers with water, dry covers with rock or soil, and/or covers with the use of geosynthetic membranes [48].

5.3. Mitigation and Monitoring of Acid Rock Drainage

In case AMD is generated in a tailings storage facility, continuous monitoring and control measures should be applied. To reduce the negative impacts of AMD, active and passive technologies must be implemented to increase the pH and remove solutes in order to comply with local water quality regulations. These activities considerably increase the costs of the mining operation, since they must be implemented continuously throughout the life cycle of the mining project. Any seepage stream from the tailings storage facility affected by AMD must be monitored and controlled. For this, monitoring wells must be installed throughout the hydrographic basin to study the quality of aquifers and surface water flows. It is important to mention that AMD flows can last for hundreds of years or more, so the monitoring of this phenomenon must be continuous. That is why activities to guarantee the geochemical stability of a tailings deposit are key to the sustainability of the mining activity. These measures are applicable to conventional tailings storage techniques and the IPDMT technique [31].

5.4. Rehabilitation and Cover of Tailings

A fundamental aspect of the feasibility of applying a technique to store mine tailings is the closure and post-closure stage, considering the rehabilitation measures. This will influence the total cost of tailings storage during the life cycle of the project. One of the advantages of the IPDMT technique is that the construction of dams to contain the mine tailings is not required, nor is physical stabilization of slopes required. In this sense, the estimation of closure and post-closure costs may be lower for the IPDMT technique compared to conventional tailings storage techniques [14].

The successful completion of remediation activities when applying the IPDMT technique will depend on the degree of consolidation of the deposited mine tailings, in such a way that it is possible to access the upper surface of the tailings, walk and move by vehicle through it, and be able to install soil or geosynthetic covers that allow for controlling the entry of oxygen, preventing wind and hydraulic erosion, avoiding contact with rainwater, etc. [6].

6. In-Pit Disposal of Mine Tailings: A Cost Estimate

A relevant aspect to consider when carrying out a comparative study of the application of different technologies for the storage of mine tailings is the cost estimate. For example, according to data from various tailings management projects, the following operating costs (OPEX) per tonne of tailings transported from the processing plant to the TSF were found:

- Conventional tailings: 1.0 US$/tonne
- Thickened tailings: 2.0 US$/tonne
- Paste tailings: 3.0 US$/tonne
- Filtered tailings: 4.0 US$/tonne
- IPDMT: 2.5 US$/tonne

The capital costs (CAPEX) of a TSF can be variable, and depend on the facilities (civil works, dam construction, drainage system, perimeter channels, etc.) and mechanical equipment considered (hydrocyclones, thickeners, pumps, filters, etc.), which is why they are not presented in this chapter.

Finally, Table 2 shows an evaluation of the mine closure costs, considering the storage of 1000 million tons of tailings with the use of different tailings storage technologies, for conventional/thickened/paste/filtered/IPDMT TSF mine closure methods.

Table 2. Conventional/thickened/paste/filtered/IPDMT TSF mine closure cost estimate: a comparative analysis.

TSF Characteristics (M: Millions)	Conventional TSF	Thickened TSF	Paste TSF	Filtered TSF	IPDMT
Throughput/Mine lifetime (mtpd/years)	50,000/20	50,000/20	50,000/20	50,000/20	50,000/20
Tailings Dry Density (t/m^3)	1.3	1.6	1.8	2.0	1.5
TSF Capacity/Footprint (Mt/Mm^3/Km^2)	1000/769/10	1000/625/7	1000/556/4	1000/500/2	1000/667/3
Number of TSF Sites (Impoundment/Dry Stack/IPDMT)	2/0/0	2/0/0	1/0/0	0/1/0	0/0/1
Max. TSF Height (Dam or Dry Stack or IPDMT) (m)	100	65	50	20	100
Total Mine Closure Cost (MUS$)	125	80	60	30	55

From the table, it is possible to identify that the highest mine closure costs correspond to the use of conventional tailings technology, where there are high-altitude dams. On the other hand, the most economical mine closure costs are for percolated tailings technology, where dam construction is not required, since the percolated tailings material behaves like a self-supporting compacted fill. Finally, it can be seen that the IPDMT technique has an intermediate mine closure cost, so is still an attractive option since it does not require major investments in slope stability, covers, and mitigation of acid mine drainage (AMD).

7. In-Pit Disposal of Mine Tailings—State of Practice

Table 3 summarizes some operations that have implemented the in-pit disposal of mine tailings; the main characteristics and data are provided.

Table 3. In-pit tailings disposal cases worldwide.

IPDMT Name	Country	Tailings Throughput (mtpd)	Solid Content (C_w)	OpenPit Mine Status
Rabbit Lake	Canada	30,000	30/(U)	Closure
Antapaccay	Peru	70,000	58/(Cu)	Operation
Ekati—Beartooth	Canada	20,000	35/(K)	Operation
Tapian (*)	Philippines	30,000	35/(Cu)	Rehabilitation

Nomenclature: Cw: Tailings Solid Content by Weight, TT: Total Tailings, U: Uranium Tailings, K: Kimberlite Tailings, Cu: Copper Tailings, (*): Failure IPDMT case.

7.1. Antapaccay Mine Case—An In-Pit Tailings Storage Facility in Cuzco, Peru

The Tintaya copper mining operation, currently operated by Glencore, is located in the province of Espinar in the department of Cusco in Peru, at an altitude of approximately 4100 m a.s.l. The mining operation has an open pit and began in 1985; the owners are considering a closing date of 2040, with two inactive tailings deposits already in the closing stage. Currently, the Tintaya mining project has been expanded to a new mineralized zone called Antapaccay. There are two open pits created by blasting and ore hauling. The minerals are transported by conveyor belt to the concentrator plant located in Tintaya. Copper concentrates and mine tailings are produced at this location. Since the old Tintaya tailings deposits are in the closure stage, the new tailings generated by the Antapaccay ore are deposited in the old Tintaya open pit [37].

The Antapaccay deposit, corresponding to the expansion of the Tintaya mining project, is 10 km southwest of the Tintaya open pit. This Brownfield-type mining project has a mineral treatment production of around 70,000 mtpd. All mine tailings generated by the Antapaccay deposit are expected to be stored until the old Tintaya open pit is completely filled. Once the mine tailings are obtained at the Tintaya concentrator plant, the tailings are transferred to two high-density thickeners to recover a large part of the water and thus reuse it in the metallurgical process [37].

Both the Antapaccay and Tintaya deposits (Figure 12) have caused socioenvironmental conflicts with neighbouring communities, which claim to live in an environment free of contamination. In this context, the management opted to carry out the deposit of tailings in the old Tintaya open pit, and thus avoid building a new tailings deposit with dams, thereby reducing the ecological footprint of the mining project and potential impacts on the water quality of the basins and on air quality due to the emission of particulate matter [37].

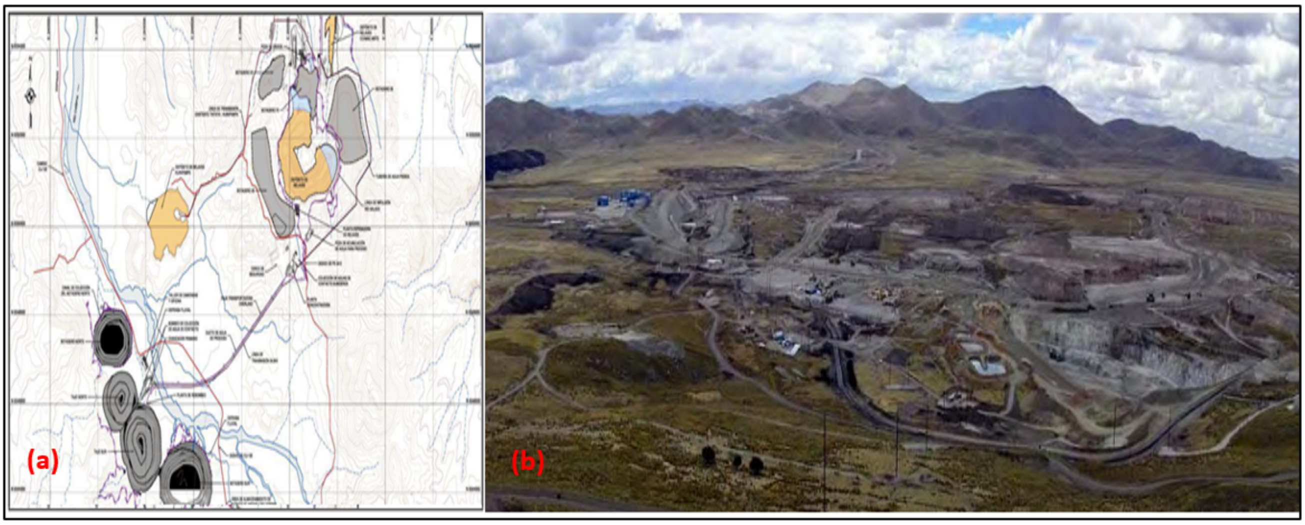

Figure 12. Antapaccay mining project: (**a**) project layout. (**b**) Old Tintaya mining project map.

Currently, 70,000 mtpd of tailings are dewatered at Cw 58% by two high-density thickeners (HDT) with a 60 m diameter, located near the Tintaya old open pit. Subsequently, thickened tailings are pumped into the Tintaya old open pit through steel pipes (Figures 13 and 14), which have choke stations at pipelines (ceramic rings) to dissipate energy in the discharge of tailings [37].

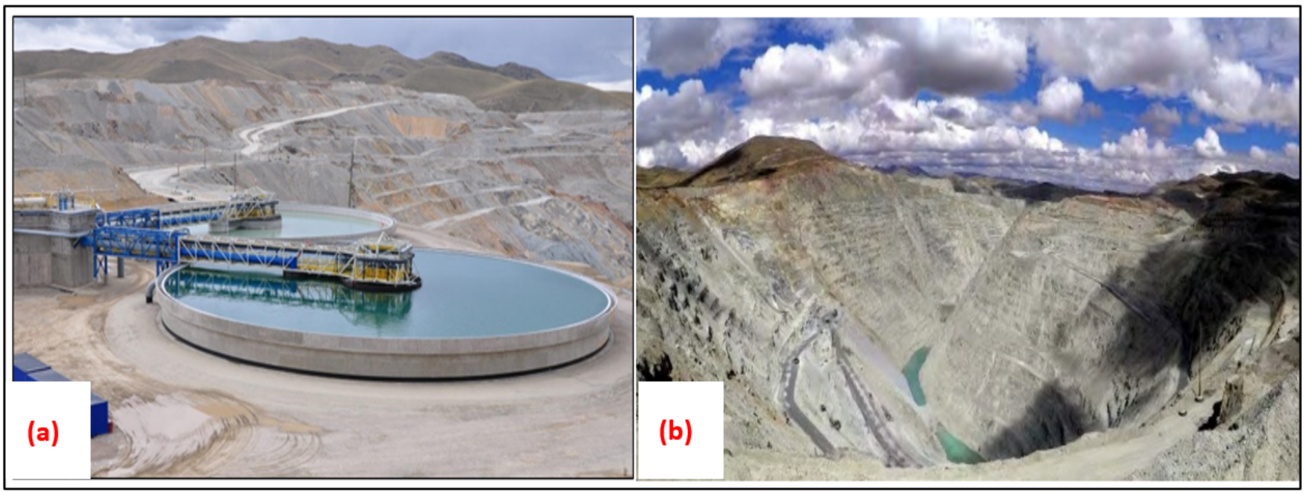

Figure 13. (**a**) Antapaccay IPDMT high-density tailings thickeners (HDT). (**b**) Old Tintaya open-pit mine.

Figure 14. In-pit disposal of mine tailings and water management at old Tintaya open-pit mine.

The Antapaccay IPDMT stores 568 million tonnes of tailings, with deposition in Tintaya open pit and confining the pit mine through a containment dam formed by complementary rockfill material located in the extreme north of the pit. The approximate final tailings storage area is 350 Ha. The deposit system possesses surface water management and reclaimed barge pumps for a clear water pond. The surface system minimizes the entry of surface water through perimeter channels and reduces potential water infiltration by using a waterproofing system in the form of a sealing dam [37].

7.2. Rabbit Lake In-Pit Tailings Storage Facility, Northern Saskatchewan, Canada

The Rabbit Lake mining operation is located on the western shore of Wollaston Lake in northern Saskatchewan, Canada. The mining operation began to be developed in 1975 and remained fully exploited until 1984. At the beginning, there was a lake called Rabbit Lake, which was drained to allow access to the minerals through an open pit. The primary mineral resources of this mining operation were low-grade uranium, located superficially in crystalline bedrock with a U_2O_8 content of 0.4%. The open pit reached dimensions of 460 m long by 365 m wide and an approximate depth of 120 m [49,50].

In the 1980s, a series of engineering studies were carried out to analyse the feasibility of depositing uranium tailings in a more controlled and environmentally safe manner, reaching the conclusion that it was more convenient to store said tailings in the open pit of Rabbit Lake than deposit tailings on the surface with check dams. Finally, the Rabbit Lake open pit (Figures 15 and 16) was reconditioned to install infrastructure that allowed the deposit of mine tailings, mainly platforms and access ramps to install piping systems and access roads for workers for monitoring [49,50].

Figure 15. Rabbit Lake in-pit disposal of mine tailings—Tailings beach overview.

Figure 16. Rabbit Lake open-pit mine with tailings filling progress.

Finally, in 1982, Canadian authorities approved the deposit of uranium tailings in the Rabbit Lake open pit, thus carrying out controlled and safe handling of this type of tailings. This marked a milestone in the deposition of tailings worldwide, being one of the first mining operations to implement this technique. One of the most complex issues regarding the management of uranium tailings is the control of radiation produced by the remnants of uranium present in the tailings and the control of radon gas. In this case, both aspects were adequately controlled, avoiding environmental impacts on neighbouring communities and local ecosystems.

7.3. Ekati Mine In-Pit Tailings Storage Facility, Northwest Territories, Canada

The Ekati Diamond mining operation is located in the Northwest Territories of Canada. In the mid-1990s, the Long Lake Containment Facility (LLCF) was designed and permitted to receive processed kimberlite. The LLCF was constructed in the early 2000s and has been continuously used for over 10 years. Five cells were separated by permeable dikes with deposition into three of the cells and the remaining two being used for water quality "polishing" to meet the local water quality regulations. The processed kimberlite tailings have been deposited over the past 10 years. The literature describes alternatives for expanding the LLCF and using mined-out open pits to augment capacity [51,52].

In addition to expanding the LLCF, the use of one of the mined-out pits at the site was evaluated as an option for the ongoing deposition of processed kimberlite. The Beartooth Pit (Figures 17 and 18) was evaluated as it is available, currently permitted to receive kimberlite tailings, and the underground workings beneath the pit are no longer mined. This pit would provide additional capacity at the end of the current mine life [51,52].

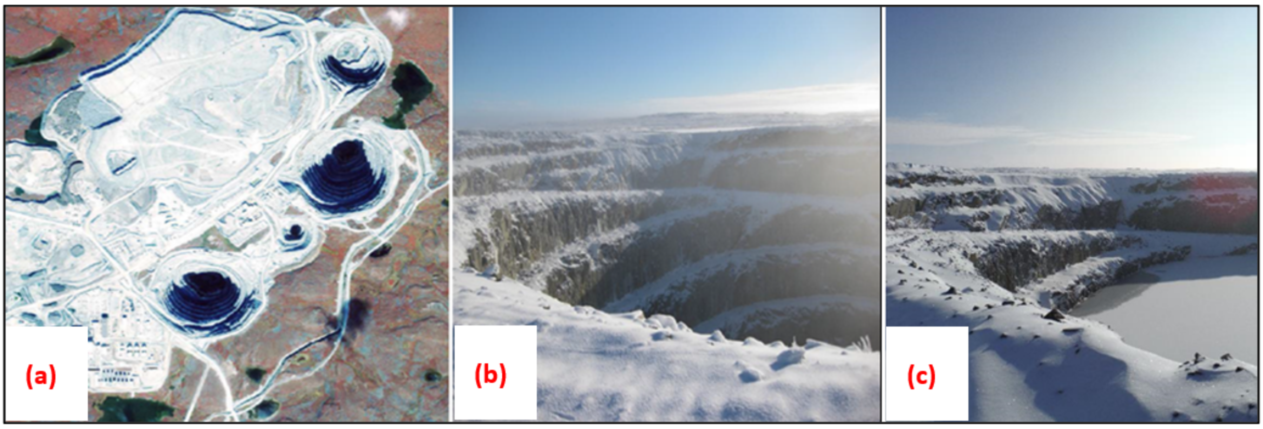

Figure 17. Ekati Mine: (**a**) overview of three open pits. (**b**) Beartooth open-pit mine without mine tailings. (**c**) Beartooth open-pit mine with mine tailings.

Figure 18. Ekati Mine: three open pits and Beartooth open pit during summer.

Beartooth open pit is currently used to deposit kimberlite processed tailings. The mine tailings are transported hydraulically by pipelines and discharged at the perimeter of the open pit through a series of spigots. The filling of the open pit with tailings is progressive over time, and the supernatant water is recovered and controlled through pumping equipment located in floating rafts. The groundwater levels in the perimeter of the open pit are constantly monitored to control both the quantity and quality of groundwater.

There are two large pits, the Koala and the Panda Pits. Underground mining is ongoing beneath these pits and, therefore, it is impractical to use them for tailings disposal. Once underground mining stops, deposition into these two pits could be undertaken in the event that additional capacity is required [51,52].

7.4. Marcopper Mine In-Pit Tailings Storage Facility, Tapian Pit, Philippines

The Marcopper copper mining operation, located on the island of Marinduque, Philippines, was designed considering the exploitation of two open pits. The open pit of this mine, called Tapian, was in operation from the 1960s until the late 1980s, while the San Antonio open pit was exploited in the 1990s [53]. In the Philippines, one of the most complex issues to manage in a controlled manner is the management of mine tailings, due to the scarcity of space available on land to store the tailings and the high level of rainfall recorded in an area with a clearly tropical climate. In 1991, at the Marcopper mine, mineral exploitation passed from the Tapian open pit to the San Antonio open pit. At that time, the tailings were being deposited in Calancan Bay and then in the Maguilaguila dam on the north side of the mine site. In the latter, there was a collapse of the containment dam, which caused spillage of tailings into local rivers. In this context, the government ordered the deposit of tailings in the old Tapian open pit. The Tapian open pit had a drainage tunnel towards the Makulapnit River. Considering the deposit of tailings in the Tapian open pit, a plug was built for the drainage tunnel to prevent the deposited tailings from escaping. After implementing IPDMT in the Tapian pit, on 24 March 1996 an accident occurred, collapsing the clogging of the drainage tunnel, producing a tailings spill in the nearby rivers, and impacting local communities and ecosystems (Figure 19). The spill of mine tailings produced by the plugging failure of the Tapian open-pit drainage tunnel was approximately 3 million cubic meters, which directly impacted communities and ecosystems in the vicinity of the Makulapnit and Boac rivers, with said tailings finally deposited in the ocean west of the island [53].

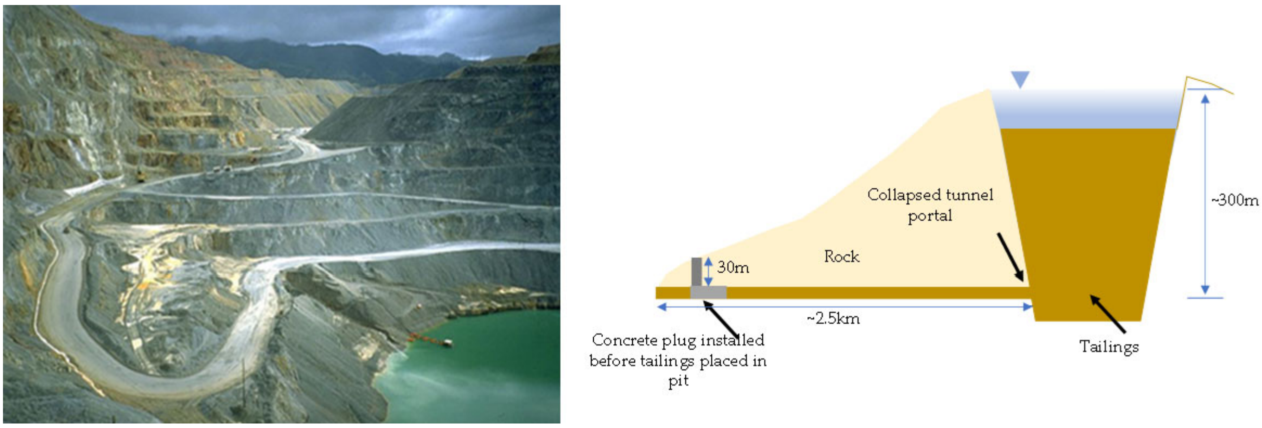

Figure 19. Tapian open pit overview and Tapian pit cross section with tunnel portal collapsed.

Due to this accident, the Marcopper copper mine ended its mineral exploitation operations in 1996. Mine waste corresponding to those mine tailings continues to enter the Mogpog River. In addition, with the passage of time, acid mine drainage (AMD) has been generated in the tailings sediment deposited at the drainage tunnel outlet and river bank, which has caused serious environmental damage. This shows that the IPDMT technique is feasible to apply, but only if there are no tunnels or underground mining works in the vicinity of the open pit, as these create a risk of collapse or potential tailings spills into the environment [53].

8. Discussion

Our consideration of the in-pit tailings disposal technique as a sustainable mine closure activity addresses the following: (i) advantages, (ii) challenges, and (iii) socioenvironmental aspects.

(i) In terms of advantages, the IPDMT technique allows for the storage of mine tailings in a controlled and safe manner as long as there are no drainage tunnels or underground mining operations in the open pit. In addition, the construction of large retaining dam structures is not required, eliminating the risks of piping and liquefaction of the dam materials. It also allows the controlled storage of tailings in a situation of record rainfall under a climate change scenario, preventing potential spills from being generated.

(ii) Regarding the challenges, it is necessary to change some conventional paradigms of the tailings deposit in the mining industry and develop new techniques that allow for the development of more environmentally friendly activities, allow a stable mine closure to be carried out, and are safe in the long term. In this sense, the IPDMT technique offers opportunities for mining operatives to carry out a closure and post-closure in a responsible manner, avoiding negative socioenvironmental impacts in the areas where the mining projects are located. The authors believe it is necessary for the mining industry to adopt innovative alternatives such as the IPDMT technique in order to achieve green solutions and sustainable mining.

In relation to (iii) socioeconomic issues, in recent years, a number of tailings deposit failures across the globe have led to a decline in public trust of mining companies and their management of tailings. Communities now demand that mining companies invest significant time and resources into tailings management facilities that utilize the best available technologies (BATs) and the best environmental practices (BEPs) to ensure safety. Additionally, communities insist on living in an environment that is free from contamination, with clean water basins, adequate air quality, and healthy soil. Implementing innovative and responsible techniques, such as in-pit disposal of mine tailings, can consistently reduce the surface area impacted by stored tailings, resulting in lower levels of seepage and particulate matter in proximity to residential areas [54–58].

In some countries, due to the lack of availability of land to deposit mine tailings on the surface with the construction of dams, the alternative of depositing mine tailings on the seabed is currently being evaluated. The promoters of this idea point out that depositing the mining tailings at the bottom of the sea eliminates the generation of acid rock drainage and would allow the tailings to be stored without the risk of dam collapse, for example, due to earthquakes [59–63]. This has generated a lot of controversy in some communities due to the potential negative environmental impacts on the ocean with respect considering the heavy metals and residues of chemical reagents that mine tailings can release. One disadvantage of depositing mining tailings at the bottom of the sea is that it becomes very difficult to reprocess these materials, and this would no longer allow the recovery of other metals of interest such as cobalt and rare earth elements (REEs) [25]. In this context, carrying out a reprocessing of the old tailings deposits and then applying the in-pit disposal of mine tailings is seen as a feasible alternative, being more environmentally friendly and stable and so considered a long-term solution for mine closure for both open-pit mines and the mine tailings [35,64].

One of the primary concerns for communities living near tailings deposits with dam heights of around 100 m or more is the risk of collapse [65–69]. This fear can be alleviated by adopting the in-pit disposal of mine tailings technique, which eliminates the need for high dams close to residential areas. By prioritizing effective tailings management and embracing innovative technologies, mining companies can safeguard the environment for future generations and rebuild public trust. Ensuring the physical and geochemical stability of a tailings storage facility in the post-closure stage is complex since many changes can occur in the physical and chemical properties of the tailings [70]. For example, in places that are seismically active, earthquakes can occur, putting the physical stability of dams at risk [71]. Climate change may manifest itself in the future with changes in the usual types of precipitation, solid or liquid, as well as in precipitation patterns, changing the magnitude, intensity, and even recurrence of precipitation events, which can significantly alter the hydrological and geochemical stability of the mine tailings [72–74]. It is for these reasons that a mine closure with the in-pit disposal of mine tailings technique is a safer and more stable option for the safety of communities and the environment. In-pit disposal of mine tailings offers a great advantage against earthquakes and climate change, improving the physical–hydrological–geochemical stability in the long term.

Considering the future use of new metals in electronic devices and renewable energy, it is likely that the trend of mining will adhere to the concepts of the circular economy, which will result in the exploitation of mineral resources at the lowest cost possible [75]. In this scenario, the reprocessing of mine tailings is the feasible alternative. If these old tailings deposits located on the surface are reprocessed, it will allow mining companies the opportunity to implement in-pit disposal of mine tailings and thus carry out safe and stable mine closure [26,76].

In particular, as it is beginning to be applied in some mining projects around the world, grinding processes are being used to separate NPAG (non-potentially acid-generating) tailings from PAG (potentially acid-generating) tailings to allow management of these process flows to increase the sustainability of the mining activity. This is how, for example, PAG tailings can be stored in an open pit and NPAG tailings can be disposed of on surfaces, thus avoiding acid drainage generation problems for neighbouring communities. This suggests that tailings management is becoming increasingly integrated with the metallurgical process. It is safe to predict that these evolving technologies and practices will continue to gain ground and become more widespread in the future [6,14].

The management of water from liquid and/or solid precipitation is an aspect to consider in terms of the physical, hydrological, and geochemical stability in the mine closure of an open pit filled with mine tailings. It is important in a post-closure stage to control and monitor the water levels inside the open-pit mine, evaluating whether it is necessary to remove water with pumping equipment and prior treatment to comply with the chemical quality indicated by specific regulations, and discharge it to the environment. In addition, it is necessary to design and implement hydraulic works such as drainage systems and perimeter channels around the open-pit mine, and thus properly manage rainwater, preventing it from coming into contact with the mine tailings inside the open pit. All of the above is relevant if we consider that a mine closure is a long-term (perpetual) solution, where under a climate change scenario there is uncertainty in the future [36,38,39].

Efficient mining closure techniques are crucial for rehabilitating and restoring sites impacted by mining activities, with the goal of reconstructing the original environmental conditions of the area. One such technique is the in-pit disposal of mine tailings method, which has the potential to restore the ground in some open-pit areas, eliminating the need for a permanent hole in the ground. Through rehabilitating the flora and fauna of the ecosystem, the site can be progressively restored to its natural state. Additionally, coverage techniques such as topsoil application, revegetation, and phytostabilization can be employed to remediate soil in the area. The in-pit disposal of mine tailings method can also significantly reduce acid rock drainage on the walls of the open pit by preventing oxidation and wetting by rainwater, leading to a more sustainable and environmentally friendly mining closure process. By embracing these techniques, mining companies can fulfil their obligation to ensure responsible and sustainable mining practices that prioritize the long-term health and safety of the environment and the community.

9. Conclusions

The authors anticipate that, over the coming decades, it will be feasible to reprocess numerous old tailings storage facilities. This will be driven by the rising price of metals, as well as new uses for metals that are currently considered to have little value, and the development of new, more efficient metallurgical technologies. Against this backdrop, in-pit disposal of mine tailings appears to be an attractive option for mine operators seeking to responsibly close down their operations. Reprocessing the mine tailings and depositing them in the open-pit could form a key part of a comprehensive site closure plan. The case studies presented in this article suggest that this technique is feasible to apply.

In recent decades, there has been a growing interest in alternative tailings management technologies, which include thickened tailings disposal (TTD), paste tailings disposal (PTD), and filtered tailings disposal (FTD). This spectrum of techniques is often referred to as the "tailings dewatering continuum" and includes some of the best available technologies (BATs) applied today in the mining industry. Although these techniques have improved tailings management in recent decades, there is still uncertainty about their performance in the long term (perpetuity), the physical, hydrological, and geochemical stability in the post-mine closure stage. The in-pit disposal of mine tailings technique is viewed as an attractive alternative from the socioenvironmental point of view for mine closure. Reductions in the emission of particulate matter, mitigation of acid mine drainage (AMD), reduction of visual impact, and physical–hydrological–geochemical stability against earthquakes and climate change are some of the advantages of applying in-pit disposal of mine tailings in the perpetual mine closure of a tailings storage facility, in site specific conditions.

While it is necessary to take some precautions to avoid generating acid mine drainage (AMD) and impacting local groundwater, in-pit disposal of mine tailings offers more competitive long-term sustainability advantages for a mine closure than tailings deposits on the surface; in addition, this IPDMT technique can be complemented by smart geochemical management practices, such as separating the mine tailings into two fractions, potential non-generators of acid drainage (NPAG) and potential generators of acid drainage (PAG), and thus properly manage the most dangerous materials to avoid negative environmental impacts.

Threats such as earthquakes and climate change must be considered in the analysis of alternative forms of disposal of mine tailings to ensure their long-term stability and security. The mine closure of a tailings storage facility should be considered in perpetuity, which is why the most sustainable techniques possible should be sought. The worldwide experience, considering all records, has taught us that large, destructive earthquakes can occur, as well as floods or extreme snowfall, for which it is necessary to be prepared by designing tailings storage facilities that are resilient to earthquakes and adaptable to climate change.

The mining industry has reached a consensus on the need to move toward a "green mining" that promotes: (i) energy and water efficiency in mine operations, (ii), reduces its environmental footprint of mine wastes and the product's life cycle, and (iii) minimizes socio-environmental impacts in the post mine closure (legacy). At the same time, green mining should develop control and measurement methods that consider the special characteristics of operations, process automation, improving work, guaranteeing worker safety and establishing circular economy practices in organizational culture.

Society's expectations of mining companies are evolving; there is a growing demand for them to adopt socially responsible policies when closing down their operations. A key aspect of this is ensuring that mine tailings are effectively managed and controlled in the long term, in order to guarantee their sustainability. To meet these expectations, innovative techniques for the rehabilitation and remediation of mining sites will become increasingly prevalent in the coming decades, facilitating responsible and sustainable mining practices.

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Abbreviations

TSF	Tailings Storage Facility
IPDMT	In-pit Disposal of Mine Tailings
BATs	Best Available Technologies
BEPs	Best Environmental Practices
REEs	Rare Earth Elements
Cw	Slurry tailings solids content by weight
TTD	Thickened Tailings Disposal
PTD	Paste Tailings Disposal
FTD	Filtered Tailings Disposal
mtpd	Metric tonnes per day
AMD	Acid Mine Drainage
PAG	Potentially Acid Generating
NPAG	Non-Potentially Acid-Generating
LLCF	Long Lake Containment Facility
HDT	High-Density Thickeners
CAPEX	Capital Costs
OPEX	Operational Costs
m a.s.l.	Meters above sea level
Ha	Hectare

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