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In-Pit Tailings Management

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Not taking risks one doesn't understand is often the best form of risk management.
—Raghuram G. Rajan, Chief Economist and Director of Research at the International Monetary Fund, 2003–2006

Increasingly widespread interest has grown regarding the use of depleted open pits for tailings storage, which are referred to as *in-pit tailings storage facilities* (TSFs). Recent tailings dam failures have highlighted that tailings fully contained below the ground surface within bedrock pit walls eliminates many failure mechanisms that exist for aboveground tailings facilities. However, as with any long-term waste storage option, in-pit TSFs have physical integrity and environmental risks that must be addressed in the design and through effective operations and monitoring.

BACKGROUND

Open pits are generally not designed at the outset as facilities that will be operated as in-pit TSFs. As a result, slope stability issues during TSF operations can create major safety risks, as well as disruptions to the continuity of the operation. The coupled geotechnical and hydrogeologic understanding associated with the evolution of pore pressure conditions as operations proceed in an in-pit TSF must be considered. Furthermore, risks associated with the ex-pit (i.e., outside the pit boundary) migration of impacted groundwater with contaminants of concern (CoCs) in exceedance of permitted values can be significant.

Water quality impacts can occur as a direct consequence of inadequate hydrogeologic understanding, poorly designed containment systems, tailings properties that differ from designs (e.g., permeability, geochemical reactivity), or potentially spatial or temporal changes in the broader hydrogeologic system that can induce unanticipated flow regimes. Ore bodies and mines tend to occur in geologically complex areas, which can lead to similarly complex hydrogeologic conditions. These complexities in combination with the challenges associated with lining in-pit TSFs to limit seepage from the facility create groundwater quality risks that must be overcome by effective design and operation.

Requirement 3.2 of the Global Industry Standard on Tailings Management (GTR 2020) requires that operators, when considering development of a new TSF, "undertake a

Source: Canadian Nuclear Safety Commission 2017

FIGURE 7.1 In-pit tailings deposition at the Rabbit Lake in-pit tailings management facility

multi-criteria alternatives analysis of all feasible sites, technologies and strategies for tailings management" with one of the stated goals being to "minimize the volume of tailings and water placed in external tailings facilities." This inherently indicates that operators should be seeking to place tailings in mined-out pits or underground workings. Further, Requirement 6.6 (GTR 2020) indicates that operators should "include new and emerging technologies and approaches and use the evolving knowledge in the refinement of the design, construction and operation of the tailings facility." Recognition is growing that for certain geologic and hydrogeologic conditions, in-pit TSFs represent best available technologies (BATs), and the inherent geotechnical stability of the tailings solids below grade is a major motivator for greater consideration of in-pit tailings management design options.

Historical Use

Historically, in-pit TSFs have been more widely adopted in Canada and Australia and evolved around the 1980s in both countries with the permitting of the Rabbit Lake in-pit TSF (Saskatchewan, Canada; Figure 7.1) in 1982 and at Bardoc pit (north of Kalgoorlie mine in Western Australia) in 1989 (C. Lane, personal communication). In Canada's case, the implementation of in-pit TSFs was initiated at uranium mines to minimize the catastrophic harm that a dam failure could have with the release of associated radiogenic contaminants into the environment.

Tailings are placed in exhausted open pits as a slurry, thickened or filtered, or in combination, and can occur either subaerially or subaqueously (e.g., Key Lake Deilmann tailings management facility, Saskatchewan, Canada) and with or without waste rock (Solbec mine, Quebec, Canada) or as filtered stacked tailings.

Water Management and Closure Considerations

As with most TSF designs, water management is critical to the successful implementation of in-pit TSFs, particularly from the perspective of reclaiming water entrained within the tailings at the base of the impoundment in order to capture process solutions, maximize consolidation, and minimize the hydraulic conductivity of stored tailings materials. The filling of mined-out pits presents the potential to develop post-closure conditions that are frequently preferred by stakeholders, in part because of the elimination of dam failure risks as well as the potential for topographic, site vegetation, and land uses that can be closer to pre-mining conditions.

Risk Management

Risks for in-pit TSFs are primarily associated with slope stability and groundwater contamination. Pit slope stability can create unique risks compared to aboveground TSFs. While

TABLE 7.1 Advantages and disadvantages of in-pit tailings storage facilities (TSFs)

Advantages	Disadvantages
Inherent physical stability and permanent physical isolation of solid wastes	Risks to groundwater quality associated with seepage of contaminated pore waters and long-term advective and diffusive transport associated with the tailings
Potential to utilize water cover options to store waste in anoxic conditions, thus minimizing further oxidation and associated acidification without the risks associated with the storage of water on impoundments	Continuity of mine operations can be affected by pit slope failures creating safety issues and disrupting tailings deposition
Closure outcomes that can be closer to pre-mining conditions and land uses that are more productive	Potential sterilization of resources caused by the inability to complete further mining within or underneath the pit
Reduction in the overall footprint compared to conventional or dry stack tailings	Previously mined open pits must be available for use as TSFs
Potential for lower operational and closure costs	No active underground workings can be present beneath the pit
Recycling of most water entrained in the tailings	Potential for added costs because dewatering/depressurization programs may need to continue through the operational life of the facility
Potential elimination of perpetual open water evaporation from a pit lake, which in arid climates can be significant consumptive use of water	
Minimizes the need for engineered control systems	
Potential for secondary mineral recovery from dewatering of tailings pore waters	
Eliminates risks associated with an aboveground TSF	

operators are commonly familiar with these risks during open pit mining, these risks need to be fully considered for the life cycle of the in-pit TSF. Similarly, groundwater contamination risks are comparable to those associated with aboveground TSFs, which are elaborated on in Chapter 21. However, there are also unique risks that result from below-grade tailings deposition and storage. The pit slope and groundwater quality risks are central to the design, operations, and closure, as mitigating these risks are a focal point for in-pit TSFs (Table 7.1). These risks must be weighed against the many advantages of in-pit design approaches, which can substantially reduce, or even eliminate, the likelihood of high-consequence risks associated with TSFs, as well as many other positive benefits. Broader support for these design options will likely require successful implementation and monitoring programs that further demonstrate that these risks can be managed.

Regulatory Acceptance

Regulatory acceptance of this design approach varies substantially by jurisdiction. However, the potential advantages to both mine operators and communities and society justify a robust consideration of the in-pit TSF design option when site conditions are appropriate. In-pit TSFs are already viewed as best practices in some jurisdictions (e.g., Saskatchewan, Canada) while they may not be permitted in others. Building a robust track record for the industry around in-pit TSF approaches is essential to recognizing the benefits of the approach to miners, communities, and the environment.

Recognizing the full potential of in-pit TSFs requires well-developed training materials and case studies to educate miners, regulators, and communities about the potential advantages of the approach.

PRINCIPAL DESIGN ELEMENTS

In-pit TSFs are designed with either wet or dry covers (Figure 7.2) and can include either fully or partially saturated materials and potentially a pit lake that behaves as either a flow-through system or hydraulic sink resulting from open water evaporation or pumping.

An essential consideration from both a corporate and societal perspective is the potential for sterilization of resources caused by the pit and underlying ore becoming inaccessible to further mining. Mitigating these risks requires that the spatial and vertical distribution of ore grades be well understood, and additional condemnation drilling may be warranted to affirm that reasonable prospects for eventual economic extraction are not compromised. Similarly, it should be confirmed that existing or future underground workings below or adjacent to the pit do not pose non-mitigable risks.

Evaluation of the site suitability of an in-pit TSF has a similar workflow to a conventional TSF and should include a multi-criteria alternatives evaluation for the site selection process (see Chapter 13) and a failure modes and effects analysis risk assessment (see Chapter 38). In-pit tailings management is a contemporary and burgeoning concept with which regulators and/or owners may not have previous experience. As a result, additional analysis above and beyond what is typical may be required to effectively demonstrate the environmental and social risks than for a conventional tailings facility.

Surface Water Management

Surface water management for in-pit TSFs can be quite similar to an operating mine, if access is required during operations. Under such circumstances, it may be necessary to operate and

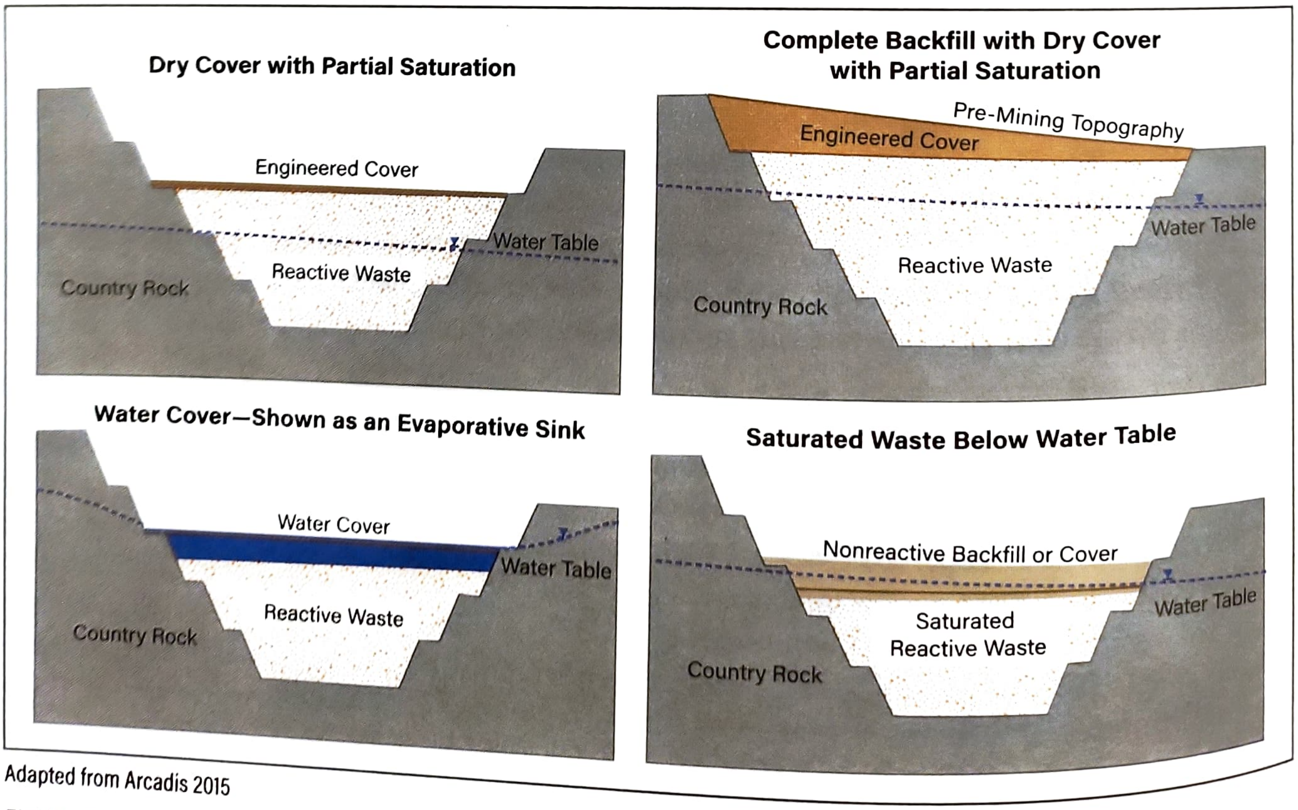


FIGURE 7.2 Examples of high-level in-pit tailings storage facility design concepts

maintain in-pit surface water management facilities including diversions, erosion controls, and surface water collection facilities. Additionally, perimeter pit diversion channels and berms to mitigate upgradient overland runoff are also critical structures to reduce water reaching the pit crest and slope and decrease the potential for infiltration, which can generate transient pore pressures and potentially slope instability.

Design storm events and rainfall-runoff analyses (see Chapter 20) are completed to support water balance models (see Chapter 29) and ensure that safe freeboard can be maintained during design storm events or combinations of events (e.g., monsoon season) within the pit crest levels or internally designed tailings cells. As during mining, minimizing the potential for erosion and back-cutting of weaker slope materials and infiltration to the pit slope and pit crest areas can be important factors for slope stability, and thus the safety and continuity of the operation.

Groundwater Management

Groundwater management is integral to a design that is protective of the environment both during tailings emplacement and post-closure. This frequently involves minimizing the flow from the pit or facilitating flow around a low-permeability tailings *core*. Development of a low-permeability core by maximizing water recovery from the tailings, which increases consolidation and decreases hydraulic conductivity, is a common design element.

The geologic and hydrogeologic conditions are key elements to evaluate as part of the design process. This includes the current and future conditions, such as the following:

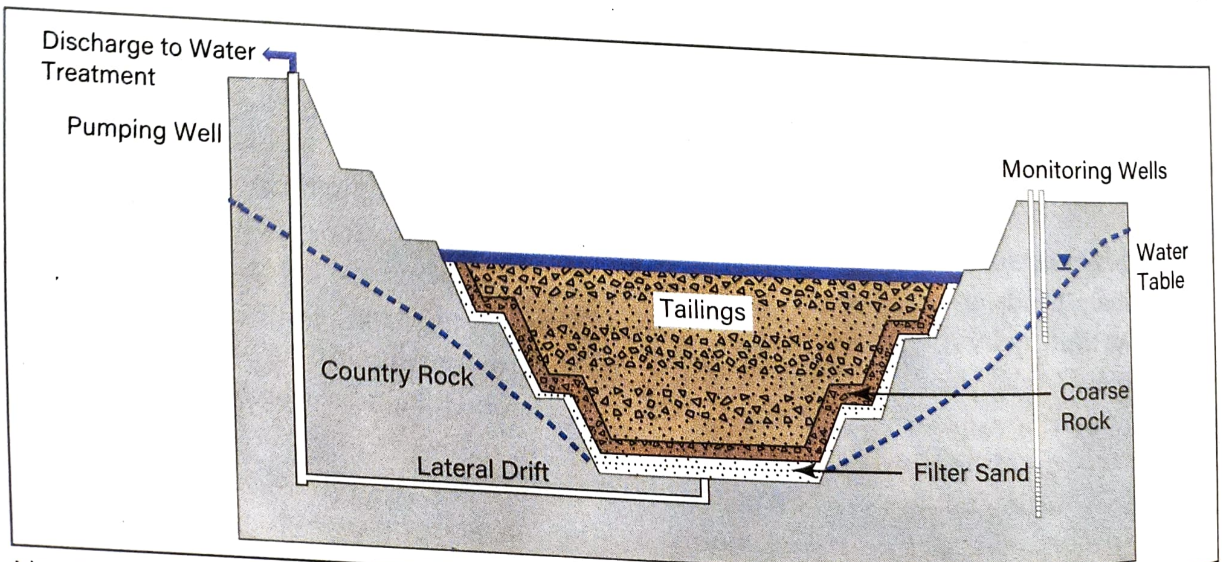
- Will the pit be in a dewatered state or flooded?
- What is pit water quality and what will it be in the future?
- How will water from dewatering be used, disposed of, or treated?
- How much water will need to be managed to maintain a dewatered state during operations (if required by design)?
- Will changes to dewatering/depressurization systems during operations induce unacceptable pore pressure conditions in the pit slopes?
- If a pit lake will be present during post-closure, will it be a hydraulic sink or will a flow-through system be created?

The baseline hydrogeologic conditions, including the hydraulic heads and water quality, are essential to have well established in the pit area, and the hydraulic properties of hydrogeologic and hydrostructural units (e.g., faults) should be well characterized. It is insufficient to only evaluate heads around the pit: It is necessary to understand the three-dimensional flow regime, vertical hydraulic gradients, and hydraulic properties of the tailings and surrounding materials. Achieving this level of understanding often requires the drilling and monitoring of nested monitoring wells or vibrating wire piezometers and targeting potential groundwater conduits with monitoring wells. The monitoring of both changes in groundwater heads and water quality during tailings placement allows for deviations from expected conditions to be rapidly identified and mitigated. Commonly, monitoring wells are constructed such that they are dual-purpose monitoring and containment wells equipped with submersible pumps on standby. Containment wells are used to provide redundancy in design and can be activated if water quality exceedances are identified.

An advantage of in-pit TSFs is the inherent hydrogeologic knowledge and understanding associated with operating a dewatering program for an open pit and geologic and hydrogeologic certainties associated with well-known fault, fracture, and lithologic contacts in what will become a TSF. Experience has shown that the level of hydrogeologic understanding at the end of mining compared to pre-mining conditions is vastly improved. As a result, compared to a potential aboveground TSF with relatively sparse drilling and hydraulic testing, the certainty with which the hydrogeologic conditions can be assessed is typically substantially greater for a mined-out pit.

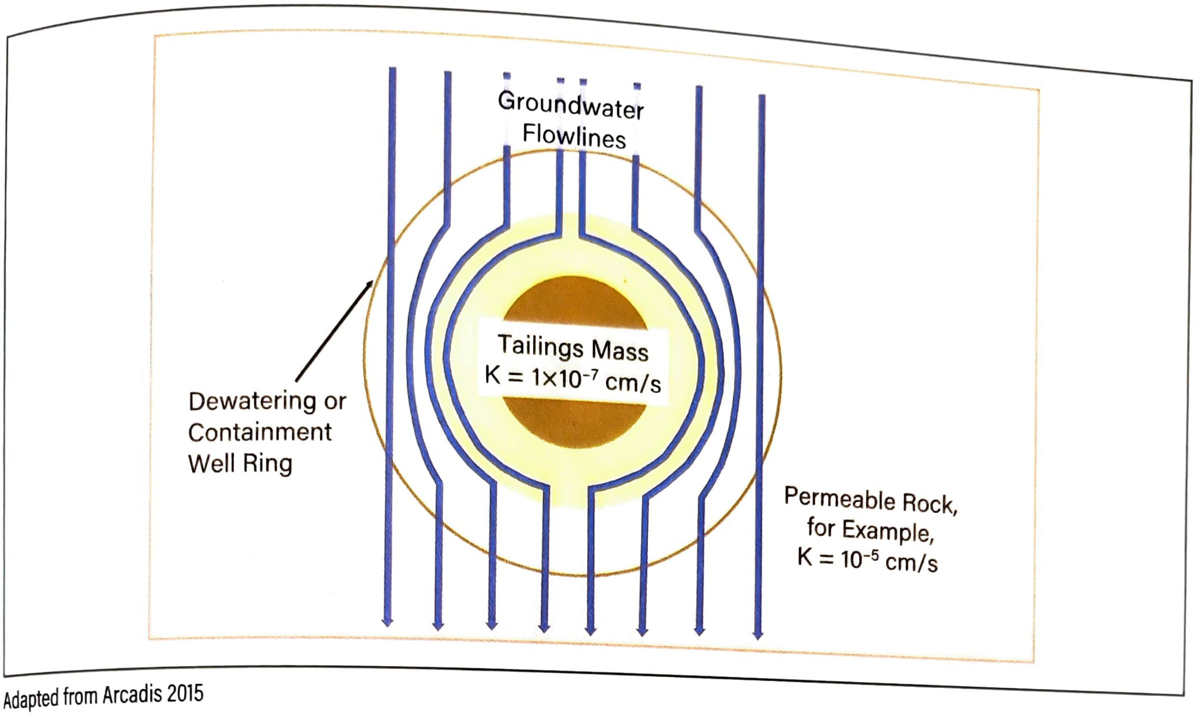
Because the suitability of the hydrogeologic conditions depends on the design strategy being implemented, there is no one ideal set of hydrogeologic conditions for an in-pit TSF. For example, while it is often desirable to have a pit that has low permeability to limit flow from the pit or more easily achieve a hydraulic sink, such conditions may create high pore pressures and increase slope stability risks as water levels in the system are permitted to rebound. To mitigate flow from the pit area, known or potential high-permeability groundwater flow conduits, such as faults, fracture zones, permeable hydrostratigraphic units, or horizontal drains, are often sealed prior to tailings placement. This can potentially be achieved by strategic application of pressure grouting of bentonite cement or clay or high-density polyethylene liners.

The concept of full or partial *pervious surrounds* (Figure 7.3) has been used at in-pit TSFs to minimize groundwater contact with the consolidated, low-permeability tailings *plugs* or cores (Cameco 2016), as well as facilitating tailings consolidation and permeability reduction by the use of a bottom drain. Conceptually, surrounding the waste with a zone of high hydraulic conductivity material lowers the hydraulic gradient flowing into the tailings and dissipates the high gradients that can otherwise develop immediately upgradient of the tailings (Figure 7.4). The pervious surround consists of a gradational increase in grain size of the pit surround from a fine sand filter at the tailings interface, to larger crushed rock at the outermost zone of the surround (Arcadis 2015). Laboratory and numerical studies (West et al. 2003) associated with the Rabbit Lake in-pit TSF that evaluated the pervious surround design concept found that it minimized



Adapted from Arcadis 2015

FIGURE 7.3 Overview of a pervious surround concept for in-pit tailings storage facilities



Adapted from Arcadis 2015

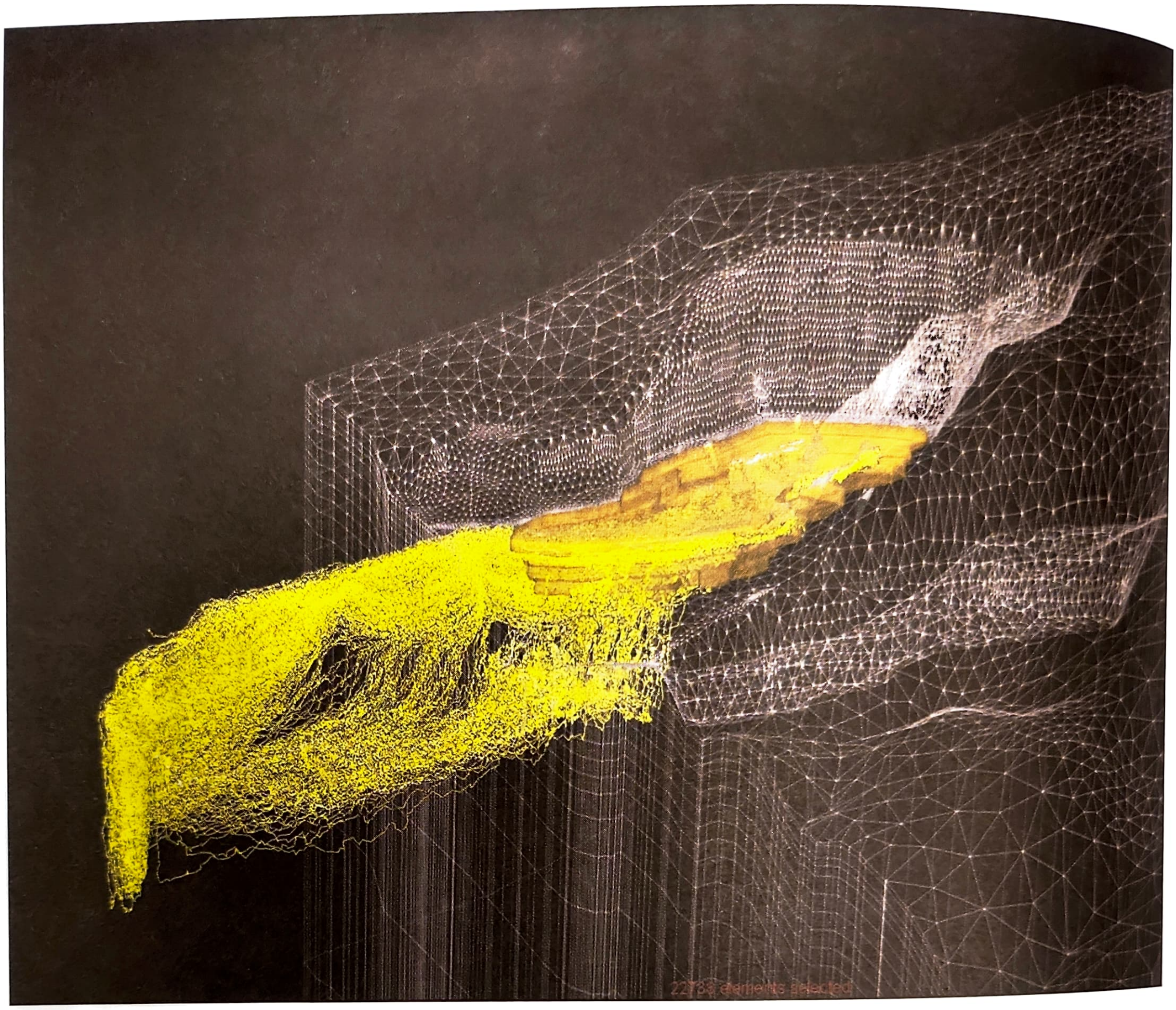
FIGURE 7.4 Concept of groundwater flow around a low-permeability tailings mass

flow through the tailings themselves, thus limiting the contaminant flux through advective processes (Lange and Van Geel 2011). The diffusive fluxes were significantly lower, and the rate of these fluxes are predicted to decline asymptotically from a rate controlled by diffusion at the tailings' outside edge toward a steady-state rate controlled by advection through their core.

In high net evaporation environments, it may be possible for a wet cover to be used that has a high enough evaporative flux that it is maintained as a hydraulic sink, inhibiting the outward migration of impacted water.

Extensive groundwater flow and transport modeling is generally required to evaluate hydrogeologic conditions during operations and post-closure, particularly the rate of re-saturation, the final phreatic surface, and groundwater flow paths and fluxes. Particle tracking (Figure 7.5) can be used to aid in identifying principal flow paths within the system and determining optimal locations and depths for groundwater monitoring. Such models can be built so that they account for consolidation of the tailings through time, which can be completed using FEFLOW (Diersch 2014), MODFLOW-USG (Panday et al. 2013), MODFLOW-SURFACT (HydroGeoLogic 1996), or similar codes. Numerical modeling approaches and hydraulic containment are described in more detail in the section on seepage analysis in Chapter 21 of this handbook, in Anderson et al. (2015), and by the National Research Council (2013).

Post-closure groundwater quality monitoring strategies change as the flow regime changes and backfilled materials re-saturate. Real-time monitoring of indicator water quality parameters (e.g., electrical conductivity) can be particularly useful in the early identification of water quality excursions. Should excursions occur and hydraulic containment wells be activated, consideration for how impacted water would be managed is required, particularly if it can no longer be used as makeup water or easily treated. Such considerations can be rather complex, and certain hydrogeologic circumstances and contaminants may result in exceedances not materializing until many years after closure (e.g., tens to hundreds of years).



Courtesy of M. Gabora

FIGURE 7.5 Example of random walk particle traces generated in a groundwater flow model from a theoretical in-pit tailings storage facility

Geochemical Considerations

The geochemistry of the tailings materials is a crucial input in the evaluation of in-pit TSF alternatives and designs. One of the primary geochemical advantages of in-pit TSFs is that they provide a mechanism to create a water cover that is inherently stable. Given the BAT objective of "eliminating surface water from the impoundment" (Morgenstern et al. 2015) and the desire to use water covers for tailings in some systems that are acid generating, in-pit TSFs can be advantageous for acid-generating materials. During operations, runoff from the pit walls requires management and potential treatment and therefore requires an appropriate level of characterization as described in standard industry references such as the *Global Acid Rock Drainage (GARD) Guide* (INAP 2014) and *Prediction Manual for Drainage Chemistry from Sulphidic Geologic Materials* (Price 2009). Classification of the tailings and pit wall materials as acid or potentially acid generating and the potential for metals or leaching of metals or other CoCs are primary factors in design evaluations, as discussed in Chapter 24.

Typical considerations on the implications of geochemistry on design, operations, and closure of in-pit TSFs include elements such as

- The physical and chemical composition of the deposited tailings, including predictions related to tailings pore water quality and CoCs (e.g., arsenic, cyanide);
- Changes in physical and chemical properties of tailings through time and related predictions on long-term water quality associated with flow through the tailings and advective and diffuse transport from the tailings materials to the surrounding materials or in a post-closure pit lake;
- The need or strategy for pre- and/or post-depositional neutralization;
- Availability of water treatment during operations and closure;
- Potential for biological neutralization;
- Tailings deposition methods, including particle size and segregation; and
- Strategies for minimizing oxygen and infiltration through dry covers.

Pit Slope Stability

If lining pit walls is not technically or economically feasible, introducing a conventional tailings slurry into a pit has the potential to negatively affect pit slope stability. Pits are generally designed based on planned operating conditions during mine operations and include assumptions around rock characteristics and pore pressure conditions. The slope design process for closure (van Zyl 2009) should be followed and should consider the transient nature of the site conditions. For example, considerations such as deterioration of benches and changes to dewatering and depressurization programs during operations must be addressed so that worker safety does not decrease through time during the operational life of the in-pit TSF. As a result, pit wall stability is a critical element of an in-pit TSF design to assure worker safety and the continuity of TSF operations.

Several key considerations are identified by van Zyl (2009) that influence the geotechnical stability of the pit walls, including the following:

- Hydrogeologic changes, such as re-pressurization of slopes caused by the cessation of dewatering and development of a pit lake;
- Weathering and slaking of certain soft rocks;
- Debris flows;
- Filling in of benches;
- Loss of access to the pit because of instability;
- Loss of surface drainage (ditches) and surface water controls;
- Undercutting of the pit wall by the pit lake erosion processes;
- Increased rockfall hazard;
- Stress relief or relaxation, resulting in instability and/or raveling;
- Seismicity; and
- Shear strength changes of pit wall materials (including intact materials, fractures, and structures).

Preventive measures may be required to inhibit entrained or free supernatant water from infiltrating high-permeability zones present in the pit. Alternatives to be considered may include

- Pre-deposition pit wall stabilization using anchors or rock fall containment blankets;
- "Dental" grouting of specific fractures or fault expressions;
- Shotcrete;

- Specific area liner (geosynthetic clay or geomembrane) usage; and,
- In situ tailings dewatering, such as subdrains, sumps, and pumps.

Underdrain

Maintaining as *dry* a tailings deposit as possible is an advantageous quantitative performance objective (QPO) in most tailings management facilities, and in-pit storage is no different. The concept of a pervious surround to provide both seepage control and pressure control within the pit walls has also been successfully implemented at Rabbit Lake mine; as described previously, the concept is based on isolating the tailings and mobile contaminants in highly consolidated low hydraulic conductivity material surrounded by a high hydraulic conductivity envelope. During operations, a hydraulic sink is maintained, and pit wall pore pressures are not directly affected by tailings placement.

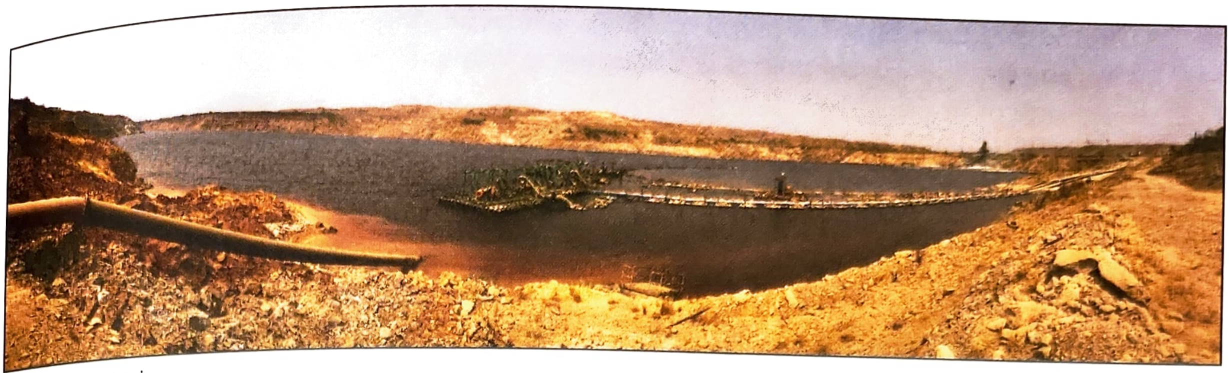
Process Water Reclaim

A conventional in-pit TSF includes a supernatant pool, similar to a conventional TSF (see Chapter 5). Minimizing the supernatant pool volume so water effectively flows to the reclaim pond improves tailings consolidation, increasing the facility's ultimate tailings storage capacity (i.e., increasing tailings dry density). Water reclaim is typically accomplished using a floating barge and pump system (Figure 7.6).

OPERATIONAL CONSIDERATIONS

Operating plans should be developed that are consistent with facility-specific QPOs. QPOs should be developed by the facility designer through consultation with the facility operators and incorporated into the operation, maintenance, and surveillance (OMS) manual. Worker safety must be paramount, and pit slope conditions should be comprehensively evaluated and monitored if worker access is required. If access is not possible, then the tailings deposition and water recovery plans need to explicitly consider this constraint. Operational considerations should be elaborated in the OMS manual and include the following:

- **Safety and access.** The tailings distribution pipeline and discharge points (spigots), supernatant pool pump barge and pipelines, and so forth, must all have safe access.
- **Tailings deposition plan.** Considerations may include circumferential versus single-point tailings deposition and/or strategies to minimize free-water contact with permeable zones in the pit walls.
- **Dewatering system.** Facilities may include tailings dewatering systems, such as wick drains or sub-tailings capture and pumping systems, to evacuate tailings bleed water and enhance tailings consolidation and decrease water quality risks associated with pore water.
- **Monitoring.** A plan should be developed to monitor facility performance against QPOs. Typical monitoring instrumentation can include
  - Standpipe or vibrating wire piezometers to measure water levels and/or pore water pressure in the tailings, pit slopes, and groundwater flow system external to the pit;
  - Water quality sampling in monitoring wells;
  - Flow measurements on inflows and outflows from the facility;
  - Inclinometers in pit walls and slope monitoring systems (e.g., synthetic aperture radar); and
  - Level sensors and freeboard monitoring of the supernatant pond.



Courtesy of K. Morrison

FIGURE 7.6 Operating in-pit tailings storage facility with a floating barge and pump system

UNIQUE CLOSURE ELEMENTS

The closure elements that are unique to in-pit TSFs are expansive because of the potential options that are available to designers as a result of the in-pit tailings management approach. An important advantage of in-pit TSFs is that the backfilled pit can potentially be designed such that the restored area is similar to the pre-mining topographic surface. Such an outcome substantially broadens the options for post-mining land use, and often regulatory agencies and communities favor not having a pit in perpetuity.

While above-grade TSFs can result in seepage during operations and draindown to groundwater, in-pit TSFs are often directly embedded within the groundwater system. As a result, there must be an understanding of the groundwater flow and transport processes associated with the tailings and the potential for long-term water quality impacts, some of which could take many years to develop. Monitoring must be completed to ensure that consolidation and permeability reductions in tailings are occurring as designed, as deviations may significantly expand the operational period and costs related to closure or potential additional mitigative actions to ensure that water quality targets are achieved.

Developing a sustainable post-closure landform should be considered in the in-pit TSF design, and the facility should be operated to achieve the closure design intent. Typically, a free-draining, evapotranspiration soil cover encapsulating the tailings deposit is preferred. When developing the cover surface grading plan, long-term tailings consolidation, which may require many years, should be considered. Designers and operators should be prepared to periodically regrade the cover surface to maintain a free-draining surface geometry. Historically, tailings covers were constructed using native soils and vegetation. More recently, geosynthetic material manufacturers have developed closure cover turfs that can be incorporated in designs to enhance or expedite tailings cover construction.

KEY POINTS

- In-pit TSFs eliminate high-consequence risks associated with catastrophic tailings dam failures.
- Risks to operations and the environment remain, principally related to pit slope stability and water quality during tailings placement, draindown, and long-term post-closure.

- A thorough understanding of pit geology, geotechnical/geomechanical characteristics, hydrogeology, and geochemistry is necessary to mitigate risks in the design, operation, and closure of in-pit TSFs.
- In-pit TSF design approaches provide the potential to transform the liability of a legacy pit into an asset that can potentially reduce costs and provide greater protection to downstream communities, water resources, and the environment.
- Recognizing the full potential of in-pit TSFs requires well-developed training materials and case studies to educate regulators and communities about the potential advantages and disadvantages of the approach.

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