GEOTECHNICAL INNOVATION, DEVELOPMENT, COLLABORATION

THE UNIVERSITY OF QUEENSLAND AUSTRALIA

FUNDAMENTALS OF HEAP AND DUMP LEACHING©

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1 Introduction

Modern heap leach facilities (HLFs) are among the largest engineered structures in mining, capable of safely processing vast, low-grade copper, gold and other ore deposits. Experience has shown that the most successful operations have integrated design and operations across the key disciplines of hydrometallurgy, hydrogeology, and geotechnical engineering. This look into the fundamentals of a multi-disciplinary approach was driven in part by the two catastrophic failures of 2024: the Çöpler HLF in Türkiye and the Eagle Gold HLF in Yukon, Canada. This paper examines the physical and chemical principles governing ore stacking and solution flow, followed by ore characterisation and its influence on hydraulic conductivity (also commonly called permeability), stability and recovery. Geotechnical considerations, including heap stability, foundation preparation and drainage, are discussed alongside hydrogeological controls on infiltration, phreatic levels and containment. Metallurgical fundamentals cover lixiviant selection, leach kinetics, recovery processes and their impact on geotechnical and hydrogeological performance. This paper also outlines pad construction methods, irrigation and aeration strategies, operational monitoring, environmental safeguards and closure principles, establishing a technical foundation for the readers to take a deeper dive into the detailed design and operational requirements of complex HLFs.

Due to the considerable overlap in terminology between heap and dump leaching, the terms heap or heap leach, as well as HLF, will generally refer herein to both heap and dump leach facilities.

2 Principles of Heap and Dump Leaching

2.1 Overview

Heap and dump leaching facilities typically consist of a lined leach pad, one or more large ponds (which are critical for solution management), an ore preparation system that can include a crushing and agglomeration system, a downstream processing plant, a water supply system to accommodate production needs and some system to stack and irrigate ore on the leach pad. The irrigation solution is a dilute solvent selected for the targeted mineral: high-pH cyanide for precious metals or low-pH sulfuric acid for copper and nickel. Most heap and dump leach facilities target metals such as gold, silver, copper and, to a lesser extent, nickel, though other targeted metals or minerals have been heap-leached, including nitrates and iodine in Chile, uranium in Australia, Niger and Namibia and rare earth minerals in Argentina. While copper, gold and silver heap leaching produce metals as the product, uranium leaching produces concentrated triuranium octoxide (U_3O_8), or yellowcake, and nickel laterite leach operations produce hydroxide or sulfide precipitates generally containing both nickel and cobalt.

The key differences between heap and dump (or run-of-mine [ROM]) leaching are related to the levels of processing and control as well as the maximum particle size. Table 1 provides a brief summary of each. Also, when ROM ore is used, the distinction between the terms "dump"

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and “heap” is sometimes ignored; in Chile these facilities are simply called “*pilas* ROM” or ROM piles.

Table 1: Heap, dump and ROM leaching

Facility Type	Key Attributes
Heap leach facility	Ore stacked in thinner lifts, usually crushed, sometimes agglomerated, under relatively tight process controls, stacked with trucks or conveyor-fed stackers
ROM leach facility	ROM ore stacked in either a heap or dump leach facility
Dump leach facility	ROM ore stacked in thicker lifts with no preprocessing such as agglomeration, generally loose process controls, low irrigation rates and longer leach cycles

Heap leach facilities (HLFs) come in a variety of shapes and sizes, generally divided into dynamic and permanent heaps. Dynamic heaps are most commonly stacked as a single lift, then leached, rinsed and removed before the next lift is stacked. The heap leach pads (HLPs) for dynamic heaps, sometimes called on-off pads, are relatively flat and rectangular. Permanent heaps are stacked in lifts, with each lift leached, rinsed, drained and then the next lift stacked on top of the previous one. The HLPs for permanent heaps come in a range of styles, often categorized as conventional HLPs or valley (or valley-fill) leach pads (VLPs). Conventional HLPs are constructed on relatively flat or gently rolling terrain, while VLPs are constructed in natural valleys with topographic confinement typical for all but one slope of the heap. The type of leach pad and heap affects the performance of the facility as well as the structural stability of both the pad and heap. This is reflected in the Heap and Dump Leach Pile Stability Rating and Hazard Classification System® (Smith et al. 2025). Agglomeration of crushed ore is often used to improve the physical properties of the material stacked in the heap, as well as to more uniformly distribute the reagents and start the leaching process sooner (i.e., at the agglomerator itself).

Ore can be stacked with haul trucks (typically the only practical option for ROM heaps or dumps) or a variety of conveyor systems, as discussed in sections 2.3 and 4.4.

2.2 Process Fundamentals

Heap and dump leaching share a sequence of steps: ore stacking, solution irrigation, percolation through the ore mass or pile, collection of the pregnant leach solution (PLS) and downstream metal recovery. While the geotechnical engineer’s primary focus is the structural integrity of the facility, understanding these fundamental processes is essential. Each step imposes unique hydraulic and geomechanical stresses on the heap or dump, influencing pore pressures, settlement, slope stability and permeability. Integration of these processes into geotechnical practice allows for designs that not only support metallurgical performance but also safeguard long-term facility reliability and stability.

In crushed ore heap leaching, the ore is crushed to increase exposure of minerals and thus improve both the leaching rate or kinetics (figures 1 and 2), and the ultimate metal recovery (Lwambiyi et al. 2009; Marsden and Botz 2017; Botz and Marsden 2019). Crushing generally produces a more uniform product but can reduce the overall permeability. In the extreme, the reduction in permeability related to increasing fineness of the gradation can lead to a reduction in metal recovery.

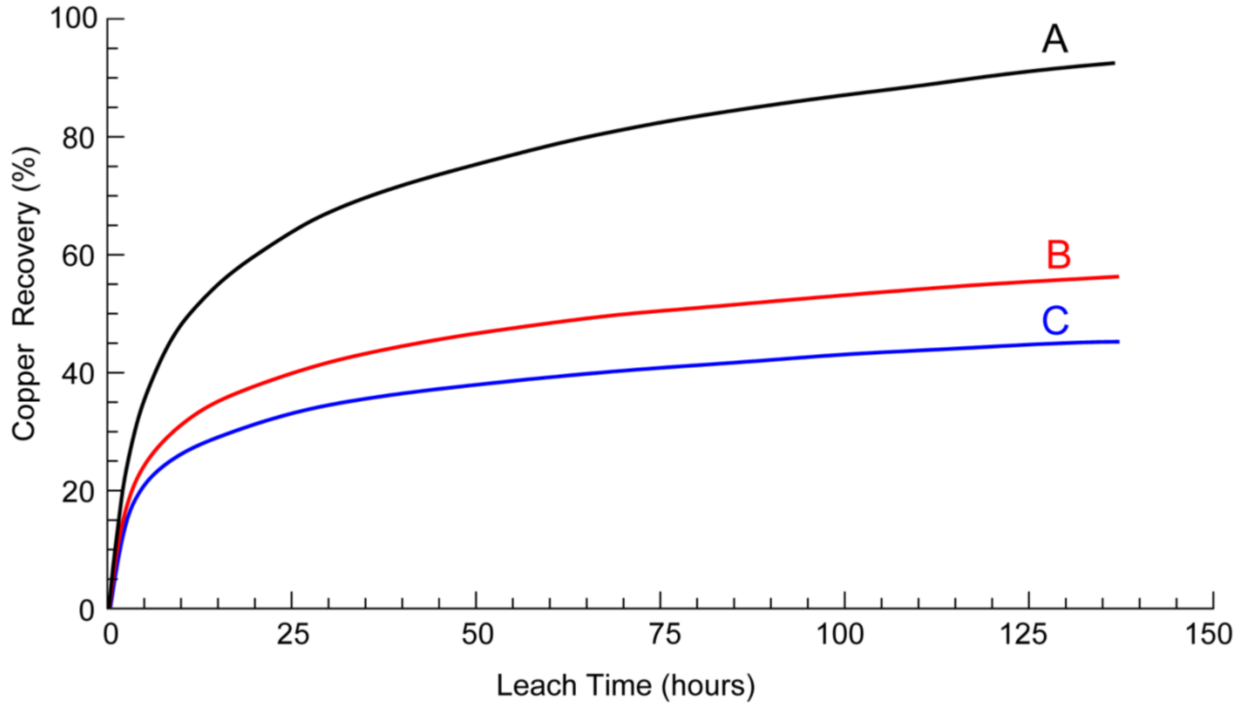

Figure 1: Malachite and atacamite copper ore leached at 60 g/L sulfuric acid (H_2SO_4) at average particle sizes (D_{50}) of (A) 3.7, (B) 11.5 and (C) 17.8 mm (after Lwambiyi et al. 2009)

Dump and run-of-mine heap leach facilities share the same fundamental characteristic: ore is stacked without pretreatment, meaning without prior crushing or agglomeration. No universally accepted definition formally distinguishes the two facility types; the primary distinguishing criterion is lift thickness, as discussed below. Because ROM ore contains a wide range of particle sizes, including large rocks that cannot be reliably conveyed, truck dumping is the only practical stacking method for both configurations.

The two facility types differ principally in the following operational and design characteristics:

- **Lift thickness.** Heap leach lifts are typically 5 to 12 m thick; dump leach lifts generally have a thickness of 15 m or greater.
- **Bench geometry.** Heap leach facilities often incorporate wider and more frequent inter-lift benches to reduce the overall slope angle of the stacked mass and limit the height of repose angle slopes.
- **Ore placement method.** Trucks may either discharge ore directly onto the active stacking face, which is more common with dumps than heaps, or deposit it at a short distance from the crest (tipping short), then a dozer pushes the material over the edge. Tipping short can reduce particle segregation, promote a more uniform particle size distribution, and reduce the likelihood of preferential flow path development.
- **Lime addition.** For precious metal applications using high-pH leach solutions, lime may be added directly to each truck load prior to dumping. While this is a less efficient method of introducing alkalinity than alternatives such as agglomeration, it can improve pH uniformity within the heap. This is true for both dump and ROM heaps, but with the thinner lifts typical of heaps the lime distribution will be more uniform.

- **Flow behaviour.** Dump leach facilities tend to exhibit greater flow localisation due to coarser and more heterogeneous particle size distributions, whereas heap leach facilities generally achieve a more uniform distribution of irrigation solution through the ore mass.
- **Leach pad design.** Historically, some copper dump leach piles were constructed directly on natural ground, with minimal site preparation and no engineered liner system. Most of these legacy facilities have since been closed or retrofitted to meet contemporary design standards.

The principal advantages of ROM (dump or heap) leaching are the substantially reduced capital and operating costs compared with conventional crushed ore heap leach facilities, thus enabling economic processing of lower-grade ore. These facilities also tend to exhibit higher shear strength and greater bulk permeability than their crushed-ore counterparts, and ROM piles are generally less susceptible to the mobilisation of undrained shear strength and, in the extreme, liquefaction.

The principal disadvantages include lower overall metal recovery and reduced control over metallurgical, hydrogeological and geotechnical performance. The potential for the development of strong preferential flow pathways is an inherent risk in ROM facilities, which can significantly reduce solution-ore contact efficiency and compromise overall leach performance.

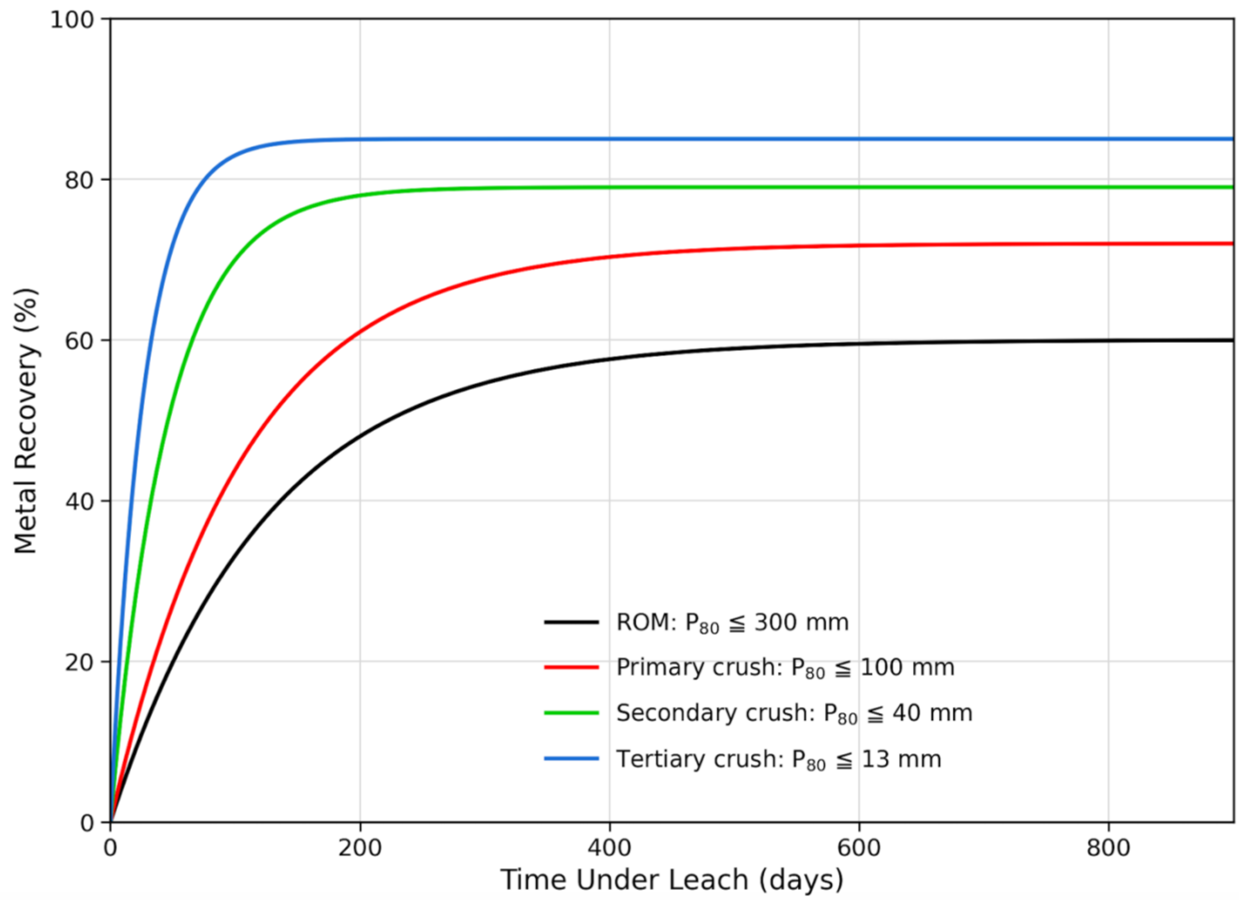

Figure 2: Leach extraction recovery for gold or oxide copper ores (after Marsden and Botz 2017)

2.3 Ore Stacking

Stacking is the physical foundation of every heap or dump leach facility. Lift thickness, orientation, placement method and sequence can influence how stresses are distributed and how fluids later migrate through the pile. Truck-dumped ROM ore stacked in thick lifts may generate coarse, heterogeneous structures with robust shear strength but poor solution uniformity, while thin-lift conveyor-stacked crushed ore (especially agglomerated) can create more uniform solution distribution (though sometimes with an overall lower permeability). Agglomeration further modifies material behaviour, improving permeability (and thus solution percolation) but also altering density and potential settlement.

Stacking methods can be grouped by stacking equipment and the direction of advancement of the lift with respect to the stacking equipment:

- **Equipment options:** primarily radial stackers fed by mobile conveyers such as grasshoppers, shiftable conveyers feeding a spreader system and haul trucks
- **Stacking directions**: advance, with stacking from the top of the lift being stacked, and retreat, with the stacker situated on top of the leach pad or the previous lift and retreating as the new lift advances

This is discussed in more detail in Section 4.4 and presented in figures 14 through 17.

2.4 Solution Irrigation and Flow Behaviour

The irrigation system drives the hydraulic regime within a leach pile. Design choices — emitters, sprinklers, wobblers, gravity or injection wells (Seal et al. 2011) — determine how evenly solutions are applied and how phreatic surfaces evolve. Over-application can damage agglomerates, generate perched water tables, reduce shear strength through mobilisation of undrained strength and, in extreme cases, trigger liquefaction. Conversely, under-application can slow leach kinetics; for example, in nickel laterite leaching, the nickel production is a direct function of the acid put through the heap, and one common operating metric is the correlation between acid input and nickel production (both in kg/t of ore). Pulse irrigation and variable application strategies can mitigate these risks, but they require geotechnical awareness of how flow patterns interact with slopes and liners. Thus, irrigation is both a metallurgical driver and a stability control mechanism.

Once introduced, leach solutions move through the heap under gravity and capillary forces, dissolving valuable metals along the way. Flow patterns are influenced by ore mineralogy, grain size distribution, compaction and segregation. Non-uniform percolation can create bypass zones that leave ore under-leached, causing reduced recovery and slower kinetics, while high degrees of saturation can elevate pore pressures and compromise structural integrity. Monitoring inflow-outflow balances, drainage efficiency and pore pressure response is therefore critical for detecting hydrologic changes that might precede geotechnical failure. The geotechnical engineer’s ability to anticipate and manage these dynamic flow regimes is central to safe, efficient leach operations. The key argument here is the importance of breaking this simplistic view of a homogeneously distributed flow throughout the heap. Geophysical techniques, as well as drilling campaigns, have shown the strong heterogeneity of this type of infrastructure, and the failure to recognise such, has been at the root of several poorly performing facilities.

2.5 The Importance of Process Fundamentals to Geotechnical Practice

Geotechnical, hydrogeological and metallurgical systems in heap and dump leaching are tightly interconnected, and none should be evaluated in isolation. There is perhaps no better evidence of this than the long history of liquefaction failures in heap leach and leached ore (called ripios in Chile and Perú) dumps, culminating in the two catastrophic failures of 2024. Heap leach facilities can create the perfect storm for such failures, with the combination of loosely stacked (and thus contractive) ore and irrigation and solution collection systems that can create relatively high local degrees of saturation. With saturated, contractive granular material in place, the only missing element is a trigger event. Triggers can take the form of a strong earthquake such as the one that caused the Cuajone, Perú, copper HLF liquefaction failure (PEER 2001), the first documented liquefaction failure in the heap leaching industry, or a variety of static loading changes such as occurred in 2024 (Smith and Konrad 2025).

Ore preparation, through crushing, screening, blending and agglomeration, alters particle size distribution, density and bonding. These changes directly affect hydraulic conductivity or permeability, compaction and the potential for contractive or liquefied behaviour under load. Poorly agglomerated or fines-rich material reduces drainage capacity, elevates saturation, promotes non-uniform solution distribution within the heap and can create undrained conditions; coarser, stronger ore generally maintains more robust geotechnical properties, but segregation during stacking (especially truck dumping) can create preferential flow paths. Oxygen is necessary in the leaching of copper ores and other sulfide-rich ores, and is often introduced by induced airflow, usually in an up-flow direction, counter-current to the solution flow direction.

Stacking methods further influence performance. Lift thickness, placement direction and loading rate govern stress distribution, slope geometry and interaction with liners. These operational decisions determine not only stability but also the uniformity of solution flow and recovery. Similarly, irrigation establishes phreatic levels and pore pressures within the heap. Overapplication or poor distribution can mobilise undrained shear strengths and compromise stability, while controlled application can enhance both recovery and safety.

Solution chemistry adds another dimension. Gold and silver heaps leached with alkaline cyanide solutions typically undergo minimal mechanical degradation, with strength losses of only a few percent. In contrast, acid leaching for copper or nickel laterites can reduce hydraulic conductivity by orders of magnitude, degrade shear strength and even dissolve significant portions of the ore mass, as discussed in Section 3.2. These effects are cumulative over the long leach cycles typical of large facilities (Sinha et al. 2015). That said, aggressive solvents can also induce grain cementation and thus increase peak shear strength.

Downstream processing requirements, whether solvent extraction and electrowinning (SX/EW) for copper or adsorption-desorption-recovery (ADR) and Merrill-Crowe for gold and silver, influence irrigation rates (solution grade, sometimes called tenor), leach cycles and solution inventories. These demands in turn dictate the hydraulic loading and stress conditions that the geotechnical design must accommodate. Case histories show the practical consequences: declining recovery often correlates with elevated pore pressures, while visible ponding or slope seepage can signal impending instability.

The key point is that geotechnical, metallurgical and hydrogeological factors are inseparable. Facilities designed with an integrated approach achieve both metallurgical efficiency and long-term stability, while those influenced by silo effects and managed without proper integration risk operational inefficiency, environmental problems and, in the worst cases, catastrophic failure.

The operating conditions that can create grave risks should not be underestimated, as there is a tendency to push metal recovery by using higher irrigation rates and larger irrigation areas. When this is done without adequate consideration of the geotechnical behaviour, large slope failures can ensue.

3 Ore Characteristics

Understanding the physical and hydrometallurgical properties of the orebody is fundamental to the success of any heap or dump leach operation. These properties, including particle size distribution, strength, permeability, mineralogy, reagent consumption and leach kinetics, not only govern how the ore behaves when crushed, stacked and irrigated but also how it will respond over time as chemical reactions progress. Predicting variability across the orebody is equally important: changes in lithology, alteration or geochemical behaviour can shift recoveries, destabilise slopes or overload solution management systems. The consequences of misunderstanding, underestimating or simply failing to manage orebody variability are evident in recent case histories. At the Eagle Gold mine insufficient recognition of ore variability and the criticality of the solution management system in an impounding valley leach facility (VLF) contributed to a large-scale slope failure. At Cerro Verde (Perú), differing responses of oxide and secondary sulfide ores required complex leach scheduling and blending strategies, with operational efficiency closely tied to the accuracy of ore characterisation. In Chile, the disposal of ripios at most of the dynamic heap leach operations (also called on-off leach pads) revealed the risks of treating spent ore as benign waste, where inadequate understanding of residual pore pressures and chemical alteration led, and continues to lead, to slope instabilities including liquefaction flow slides (Herrera et al. 2023). These examples demonstrate that orebody characterisation is not an academic exercise, but rather a foundation for both economic success and the avoidance of costly technical and/or environmental failures.

At a less dramatic level, poor metallurgical performance is also indicative of poor geotechnical or hydrogeological behaviour. Early indicators of geotechnical problems include declining metal recovery, while more obvious signs include solution ponding on top of the heap or seepage from the slopes.

3.1 Ore Type and Mineralogy

3.1.1 Gold and Silver Ores

According to Manning and Kappes (2011), the chemistry of leaching gold and silver is essentially the same. However, silver mineralisation can be quite variable and that adds complexity to processing. As a general rule, the gold and silver in ore targeted by heap leaching should not be refractory or encapsulated in minerals such as pyrite or arsenopyrite. A dilute alkaline sodium cyanide solution dissolves both metals while leaving most gangue minerals unaffected. Maintaining the solution pH between 9.5 and 11 is critical: cyanide consumption rises sharply below about pH 9.5 (in which case cyanide can produce hydrocyanic acid, which is highly volatile and toxic), while recoveries can decline above pH 11, with carbonate and sulfate dissolution potentially causing scaling in the heap and piping as well as blinding of carbon in the adsorption-desorption-recovery (ADR) plant. Heap ores typically contain both metals, but their behaviour differs. Gold, usually a native metal, is highly soluble in weak cyanide solutions. While native silver does occur, less reactive mineral forms are the norm, including argentite, cerargyrite and embolite. As a result, heap recoveries typically range from 50 to 90% for gold compared to 25 to 60% for silver. The Rochester Mine (Nevada, USA) reports typical oxide ore recoveries of 77.7 to 85.0% for gold and 59.4 to 61.0% for silver (Coeur Mining, Inc. 2024).

Gold is usually recovered from solution by adsorption of the gold-cyanide complex onto activated carbon, followed by stripping and electrowinning to produce doré in an ADR plant. Solutions rich in silver or both metals are often treated by the Merrill-Crowe process: the solution is filtered, de-aerated and mixed with zinc dust to precipitate metals, which are then smelted to doré. Typical cyanide concentrations in heap solutions range from 100 to 600 ppm NaCN, though some ores require more than 1,000 ppm. Consumption varies from 0.1 to 1.0 kg NaCN per tonne of ore, while lime or cement additions (from about 0.5 to > 20 kg/t) maintain alkalinity and support agglomeration. Alternative lixiviants such as thiosulfate, thiourea, hypochlorite or bromine have been tested, but cyanide remains the most effective and environmentally manageable reagent for gold and silver leaching (Marsden and House 2006). While cyanide is an acutely toxic chemical, it is also naturally present in the environment and tends to degrade rapidly. The degradation products — including nitrates, nitrites and ammonia — generally warrant more attention than the cyanide.

3.1.2 Copper Ores

Copper ores processed by heap leaching fall into four broad categories: oxides, sulfates, secondary sulfides and primary sulfides. Each category has distinct metallurgical behaviour and geotechnical implications as summarised in Table 2. These metallurgical distinctions manifest directly in heap geotechnical behaviour, influencing permeability, shear strength, pore water pressure and long-term stability, as also discussed in Table 2.

Table 2: Copper ore types and leaching characteristics

Ore Type	Example Minerals	Metallurgical Implications	Geotechnical Implications	Operational Considerations
Oxides	Chrysocolla $(Cu,Al)_2H_2Si_2O_5(OH)_4{\cdot}nH_2O$, Azurite $Cu_3(CO_3)_2(OH)_2$ and Malachite $Cu_2CO_3(OH)_2$	Rapidly soluble in dilute sulfuric acid, fast leach kinetics and high recoveries	Typically, modest structural change, but some oxide ore can degrade sufficiently to affect permeability	Generally, the simplest copper ore to heap-leach, though acid consumptions can be relatively high, sometimes managed by installing liners and drainage pipes between lifts in conventional multi-lift heaps
Sulfates	Chalcanthite $CuSO_4{\cdot}5H_2O$ and Antlerite $Cu_3(SO)_4(OH)_4$	Extremely soluble copper salts, rapid kinetics that can spike solution tenor feed to the SX/EW plant	Can create zones of lower permeability and rapid pore pressure changes	Not an important ore in heap leaching, though these are found in the Atacama Desert of Chile
Secondary Sulfides	Chalcocite Cu_2S and Covellite CuS	Moderate kinetics, leaches slower than oxides or sulfates but faster to much faster than primary sulfides	Ore degradation and long-term stability issues, loss of permeability and development of excess pore pressures	Kinetics can improve with aeration or bioleaching
Primary Sulfides	Chalcopyrite CuFeS2, Bornite Cu_5FeS_4, and Enargite Cu_3AsS_4	Very slow kinetics, resistant to ambient leaching, requires oxidants, heat or bacteria	Ore degradation and long-term stability issues, loss of permeability, development of excess pore pressures and the resulting loss of shear strength	Typically processed by flotation, but bioleach technology has been commercialised (e.g., in Escondida); significantly higher oxygen demand than secondary sulfide ores

Oxide ores (malachite, azurite, chrysocolla) dissolve readily in dilute sulfuric acid, leach rapidly under ambient conditions and are well-suited to conventional heap leach and SX/EW circuits. Recoveries are generally high and ore degradation modest, though some oxide ores have high acid consumption; in multi-lift heaps, this is often managed by installing inter-lift geomembrane liners with PLS collection pipes between lifts.

Copper sulfate ores (principally chalcanthite) are highly water soluble and not a significant heap leach feed in most settings. They occur mainly in hyper-arid porphyry districts such as northern Chile (at CODELCO's Chuquicamata and Glencore's Lomas Bayas mines, for example) where they accumulate rather than dissolve and wash away as they would in wetter climates.

Secondary sulfides (chalcocite, covellite) form by supergene enrichment beneath the oxide zone. They leach more slowly than oxides or sulfates but substantially faster than primary sulfides and typically respond well to aeration and bioleaching.

Primary sulfides (chalcopyrite, bornite) are chemically resistant and leach slowly, requiring strong oxidants, elevated temperatures and often bacterial catalysis[4] (Pradhan et al. 2008). Recoveries are lower and more variable, leach cycles are long and oxygen demand is significantly higher than for secondary sulfides. In recent years, several major copper producers have introduced leaching enhancement reagents—surface-activating or depolarising agents applied in trace quantities—to improve chalcopyrite and bornite recovery.

Beyond ore mineralisation, the presence and type of clay minerals also exert important influences on both metallurgical and geotechnical performance. Engineers focus on fines content (typically defined as the fraction passing the #200 sieve), but mineralogy can be more important. An ore with 10% minus #200 fines, dominated by smectite or montmorillonite, will exhibit much lower shear strength and permeability than one with non-plastic fines. Clays may also consume reagents—carbonates increase acid consumption and sulfides consume cyanide—further complicating leach performance. Clays and clay minerals are fine-grained materials characterised by their plastic behaviour when wet. They primarily form through the weathering of silicate rocks, diagenetic reactions and hydrothermal alteration. While the definition of clays can vary across scientific disciplines, they are generally considered to be materials with a particle size < 0.002 mm, having a layered structure containing aluminium, silica and water; the layered structure is what makes the behaviour of clays markedly more complex than fine sand or silt (Foos 2024). The Unified Soil Classification System (ASTM 2020), which is the standard method used by most geotechnical engineers, defines clay as any soil with 50% or more passing the #200 sieve (0.075 mm) and a specific relationship between the various Atterberg limits (specifically, the liquid limit and plasticity index) called the A-line (Terzaghi et al. 1996). The combined physical and chemical effects of clays can be central to both metal recovery and slope stability.

The leaching process is not merely a metallurgical challenge but a multidisciplinary one, as effectively demonstrated and supported by experience in the bioleaching of primary copper sulfides at, for example, the Escondida mine in Northern Chile, which required coordinated geotechnical, hydrological and microbiological design and monitoring (Ghorbani et al. 2015; BHP 2022; Jia et al. 2024). From a metallurgical perspective, bioleaching extends recoverable copper resources well beyond oxide and secondary sulfide zones. PLSs from Escondida's sulfide heaps are processed in SX/EW circuits, producing copper cathodes. While recoveries are slower and lower than for oxide ores, the scale of the sulfide resource makes bioleaching economically feasible. Geotechnical performance is directly linked to these processes. As compared to more conventional leaching, bioleach heaps tend to operate at higher temperatures and require better aeration and solution distribution infrastructure. Maintaining permeability for oxygen transfer is essential, as compaction or fines migration can create anaerobic zones that limit bacterial activity and generate pore pressure imbalances. The long leach cycles associated with bioleaching also

4 Bacterial or microbial catalysis is the use of bacteria, or enzymes derived from bacteria, to speed specific chemical transformations.

mean structural stability must be maintained over years or even decades, which can be a challenge given the potential for extensive geochemical degradation of the ore.

Figures 3 and 4 are photos of two copper sulfide dump bioleaching and secondary crushed ROM leaching ore facilities.

3.1.3 Uranium Ores

Uranium heap leaching remains a niche but viable option for extracting uranium from low-grade ores where conventional milling is not economical. The method involves stacking crushed ore, typically grading below 0.1% U_3O_8, onto engineered pads, irrigating with acidic or alkaline lixiviants and recovering uranium from the PLS by ion exchange or solvent extraction to produce yellowcake. Recoveries of 50 to 80% are typical, depending on ore type and solution chemistry.

Commercial application has been limited. Acid heap leaching has been operated in Hungary, Niger and Australia, while carbonate-based methods have been tested in Namibia. Globally, uptake has been constrained by the dominance of in situ recovery (ISR), which offers lower costs and fewer surface facilities. Still, heap leaching retains advantages, including relatively low capital cost, modest water requirements, simplified residue handling, and, under modern designs, favourable environmental performance. In Niger, Areva (now Orano) partnered with the government on two acid heap leach projects. At Arlit, a dedicated heap pad supplemented production from conventional milling. Imouraren was planned as a large-scale heap leach, but development was suspended in 2015 following weak markets after the Fukushima nuclear accident. In Australia, Rio Tinto completed a feasibility program for a leaching operation at Ranger in the 2010s, and BHP tested small-scale trials at Olympic Dam in 2018/19.

Namibia's Trekkopje project is the best-known example of alkaline uranium heap leaching. Developed by Areva, it targeted shallow calcrete-hosted ore with grades below 0.015% U_3O_8. A pilot heap produced yellowcake in 2011, confirming carbonate/bicarbonate leach chemistry as a viable alternative where acid-sensitive gangue precludes sulfuric acid use (Mining Technology 2011; Klein 2025). However, ultra-low grades, technical novelty, and market uncertainty forced the project into care and maintenance in 2013 before commercial production. Trekkopje remains a pioneering demonstration, showing even very low-grade ores can be processed if chemistry and pad design are carefully matched.

From a geotechnical perspective, acid-leached uranium ores behave similarly to leached copper oxide ore, with some strength loss and permeability reduction. Alkaline leaching tends to cause less degradation and yield improved geotechnical performance, but some biological clogging (in the form of algae) has been noted on the surface.

3.1.4 Nickel Laterite Ores

Nearly all industry attention to heap-leaching nickel ores has been focused on lateritic deposits, in part because most of the known and undeveloped nickel resources are laterite hosted. The alternative is sulfide ores, which require more complex bioleaching to liberate the nickel, as discussed in the final paragraph of this subsection. Another driver is that most nickel laterites also contain cobalt; most cobalt production is currently limited to a few mines, and so there is broad interest in diversifying the cobalt supply.

The concept of heap-leaching nickel laterites was first proposed in the 1980s, when laboratory-scale column tests successfully recovered over 80% of total nickel from a Greek laterite deposit (Steemson and Smith 2009). In the early years of the current century, BHP extensively invested in the technology and even helped fund the Çaldağ nickel heap leach project in Türkiye, though this HLF has yet to come into production. BHP also performed significant studies on heap leaching at its Cerro Matoso nickel plant in Colombia as a parallel processing circuit to process the ore not suitable for the rotary kiln-electric furnace (RKEF) circuit. The most notable advances, however, have been made in Brazil at Brazilian Nickel Ltd's Piauí nickel-cobalt mine in São João do Piauí state (Oxley et al. 2022), which included commissioning a small-scale commercial HLF in 2022 and advancing the much larger project (nominally 25,000 dry tonnes per annum [tpa] nickel production capacity) through the feasibility stage (it has now progressed well into advanced engineering and funding). As with other metals, acid leaching of lateritic nickel ores brings with it some geotechnical and hydrogeologic complications. Several technical papers provide some details on this topic, including Smith and Steemson (2009), Sinha et al. (2015), Smith and Christie (2015) and Oxley et al. (2016).

A single nickel sulfide deposit, Talvivaara, in northern Finland, has been developed using a two-stage leaching process (a dynamic bioleach heap followed by a conventional, multi-lift heap). Talvivaara struggled in its early years, though work there continues and operations seem to be going better with nominal nickel production of 34,000 tpa. Talvivaara is currently operated by the state-supported company Terrafame. Key challenges for this project include the subarctic climate, low ore grade (0.22% Ni, 0.5% Zn, 0.13% Cu, 0.02% Co) and the difficulties inherent in bioleaching at 64° N latitude.

3.2 Geotechnical Properties

3.2.1 Particle Size Distribution

Crushed ore, typically defined by the screen or sieve size allowing 80% of the ore by weight to pass (P_{80}), is produced in two- or three-stage closed-circuit crushing systems. Crushing to a finer stage (i.e., finer P_{80} size), generally improves leach recovery and kinetics compared to coarse crushed or ROM ore. However, finer crushing can also generate more fines, particularly clay and silt, which can reduce permeability and shear strength. In some cases, the resulting material is more vulnerable to the development of undrained shear strengths and, in extreme cases, liquefaction, as observed at the Eagle Gold HLF (Smith and Konrad 2025).

Since the 2010s, high pressure grinding roll (HPGR) crushers have been employed at several heap leach projects to better liberate metals through finer crushing. This method also produces more micro-fractures in the larger particles, sometimes materially improving recovery. HPGRs require 20 to 40% less energy than conventional crushing for the same P_{80} while generally producing a more uniform product. On the other hand, because of the finer crusher and the formation of compressed fines, secondary processing such as agglomeration is more often required.

In contrast, coarse crushing, such as single-stage open-circuit systems using only jaw crushers, tends to produce ore with superior geotechnical properties, including higher permeability and shear strength and lower to much lower vulnerability to undrained behaviour. The trade-offs can include slower leach kinetics and lower ultimate metal recovery, making coarse crushing less effective metallurgically, even though it provides stability benefits and cost savings.

ROM ore presents a different set of challenges. ROM particle size distribution is usually wide, and gap grading is relatively common. The latter can promote preferential flow paths and reduce the uniformity of solution distribution, both of which are aggravated by thicker lift stacking. However, blast control in the mine can reduce these effects. Figures 3 and 4 show copper primary and secondary sulfide ROM leaches in northern Chile. In ROM heaps and dumps, the larger and finer particles can segregate during the stacking process, especially for truck dumping directly on the face of thick lifts. This can create variations in both shear strength and permeability from the top to the bottom of a lift. Further, the larger particles leach slowly and contribute little to overall metal recovery. However, for many orebodies the fine fraction contains most of the mineral value, thus mitigating the low recovery from the largest particles. Nevertheless, ROM ore piles can offer stability advantages and lower operating costs, enabling reduced cutoff grades and fuller utilisation of the orebody. For copper ROM leaching, recovery rates are typically 20 to 50% (occasionally as high as 70% for unusually favourable ores) with an industry average of under 50%. The Freeport-McMoRan Morenci copper mine in Arizona, USA, reports a range of ROM dump leach recoveries (based on ore type) of 13 to 59%, compared to crushed ore recoveries for the same ores of 13 to 83% (Freeport-McMoRan 2024), with a non-weighted average difference of 12 percentage points; this increases to 17 percentage points if the hypogene sulfides (the two lowest recoveries of six ore types) are excluded from the data.

Agglomeration of two- or three-stage crushed ore can be an effective way to manage high fines content and mitigate the effects of both plastic and non-plastic fines. Agglomeration can improve slope stability and reduce problems such as solution channelling and blinding. Where practical, binders such as Portland cement may be added to strengthen agglomerates, improving long-term performance. However, this approach is typically restricted to high pH leaching systems, such as used for gold and silver ores, or for carbonate leaching or uranium ores. Agglomeration circuits also provide a means of distributing reagents more uniformly within the ore, accelerating the leaching process and supporting more consistent metallurgical performance.

Figure 3: Copper sulfide dump bioleaching at the Morenci mine, Arizona, USA

Figure 4: Copper secondary sulfides ROM leach in northern Chile

3.2.2 Shear Strength

The shear strength of heap and dump leach ore evolves during operation as physical and chemical processes alter the as-stacked material. Initial strength depends on particle size distribution, mineralogy, rock durability and stacking method, with agglomeration sometimes providing short- or mid-term gains. Over time, irrigation, fines migration and physical and chemical degradation (especially for acid leach facilities) can reduce both friction angle and permeability, increasing the risk of both conventional slope failures and undrained behaviour.

Recent failures at Çöpler and Eagle Gold highlight the consequences of overestimating shear strength and underestimating saturation and pore pressure effects; both were relevant to the causes of each failure (Vock 2024; BusinessWire 2025; Smith and Konrad 2025). At Eagle Gold, the Independent Review Board (IRB) investigation showed the range of peak drained friction angles (34° to 38°) used in the design was far higher than the mobilised undrained strengths in the weakest ore (18° peak and 12° residual), reducing the factor of safety (FoS) and leading to failure. Such cases emphasise the need to characterise both drained and undrained behaviour and to account for variability in ore properties across lifts.

Chemical degradation is particularly significant in acid leach systems, where long-term reductions in strength and permeability have triggered slope failures in Chilean ripios dumps; Figure 5 shows liquified ripios, with the debris flow reaching more than 1 km from the stacker discharge. Effective design must therefore integrate conservative shear strength and permeability assumptions, pore pressure monitoring and ongoing calibration of geotechnical models based on actual performance.

Figure 5: Liquefied ripios at a dynamic (on-off) copper HLF in Chile located more than 1 km from the stacker discharge

3.2.3 Hydraulic Conductivity (Permeability)

In soil mechanics, hydraulic conductivity (also commonly referred to as permeability) is a measure of a porous material's ability to transmit water or other liquids through its pore spaces, representing the ease with which water or leach solution can flow under the influence of a hydraulic gradient. The terms "permeability" and "hydraulic conductivity" are used interchangeably throughout this paper and, unless otherwise specified, both refer to saturated behaviour.

Key Influences on Permeability

Permeability is influenced by several factors, including:

- Particle size distribution
- Clay content and clay mineralogy
- Heterogeneity of the heap
- Confining or overburden pressure, which increases with depth and reduces the void ratio or porosity, and thus the permeability. The degree to which permeability is affected depends on several factors including the rock strength.

- Degree of saturation. Generally, when permeability is discussed, what is meant is saturated permeability (or saturated hydraulic conductivity). However, solution flow in heaps primarily occurs in the unsaturated phase, in that heaps are typically designed to operate in the range of 50 to 65% saturation (Robertson et al. 2023). Saturated permeability is always higher than unsaturated; this is one reason designers generally want a very high ratio of the saturated permeability of the ore (typically expressed as cm/s) to the irrigation rate (as expressed in cm/s). A commonly used guideline is for the saturated permeability of the ore to be at least 10 times the irrigation rate; higher is better, with some authors recommending 100 times (Robertson et al. 2023).

A critical point is that permeability can decrease over time due to both physical degradation (e.g., compaction and fines migration) and chemical alteration of the ore during leaching. Chemical degradation is most pronounced in acid leaching systems such as those used for copper and nickel laterite ores, as well as in sulfide-containing gold and silver ores (Steemson and Smith 2009; Smith and Christie 2015; Smith 2022).

Chemical and Physical Degradation

Figures 6 and 7 illustrate the long-term effects of acid leaching on permeability (Sinha et al. 2015). In a Chilean mixed oxide-sulfide copper heap (Figure 6), three successive leach cycles with an overburden pressure equivalent to 60 m of ore show a significant decline in permeability. Similarly, Figure 7 demonstrates that permeability loss in leached copper ore varies with both depth in the heap and acid concentration. These examples underscore why designers must account for in situ permeability evolutions, not just initial laboratory results.

Scale Effects and Field Performance

Laboratory-measured permeability often substantially differs from full-scale heap behaviour. Two mechanisms help explain this gap:

- **Fines migration:** Irrigation can mobilise fine particles, causing them to migrate downward and clog pores, particularly where there are sharp changes in permeability or particle size distribution (including near drainage layers) or where hydraulic gradients are high.
- **Particle size segregation during stacking:** Different stacking methods and lift thicknesses can result in particle segregation over a wide range. Even within a stacking method, slight variations can reduce segregation, such as truck stacking using dumping short and dozer pushing versus direct dumping on the face. Regardless of the stacking method selected, heterogeneity should be addressed as it can create preferential flow paths and zones of lower permeability.

Coupling Between Permeability and Shear Strength

Permeability and shear strength, the two most important geotechnical parameters in heap leaching, are closely linked. Both decrease with increasing fineness of the particle size distribution and with increasing clay content. Further, with sufficiently low permeability, excess pore pressures can develop with a resulting reduction in available shear strength as the behaviour transitions from drained to undrained conditions. Settlement, compaction and localised collapse resulting from fines migration or internal piping (Figure 8) can also significantly modify both properties, though in opposite directions; for example, with increasing density the permeability decreases but the shear strength increases and the risk of contractive behaviour decreases.

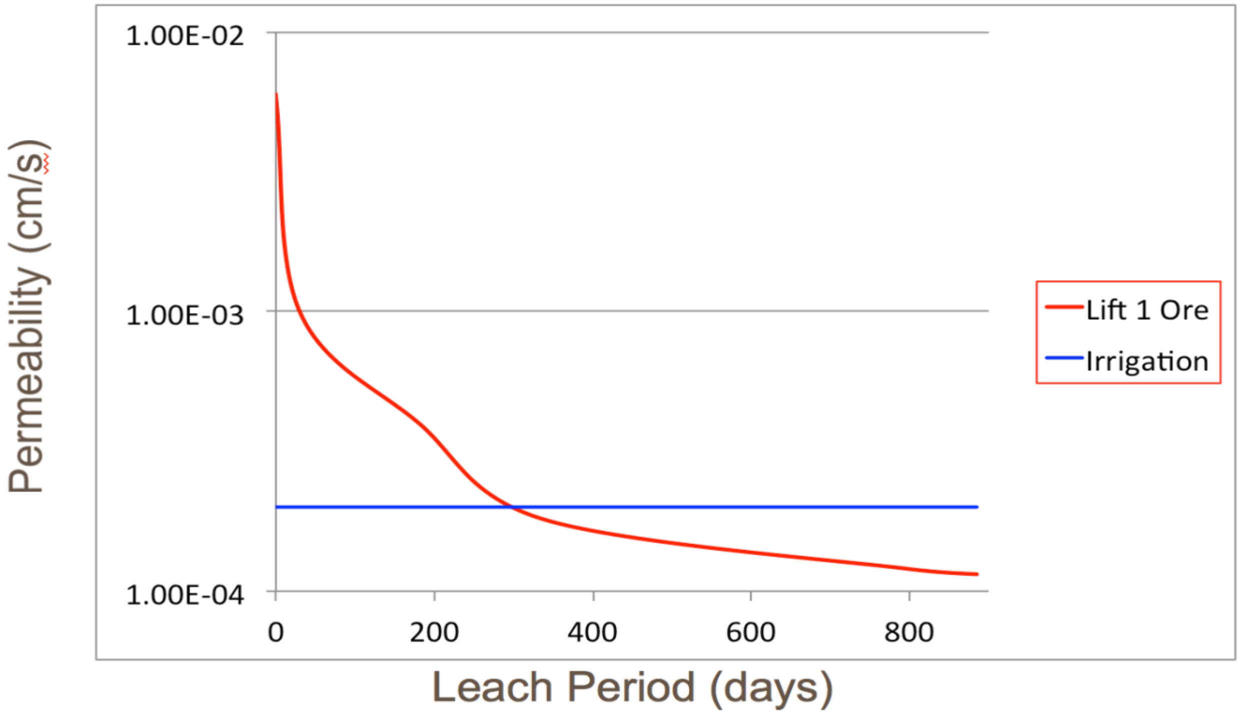

Figure 6: Permeability of a mixed oxide-sulfide ore from a Chilean copper heap leach project. The test period was three leach cycles at an equivalent overburden pressure to 60 m of ore

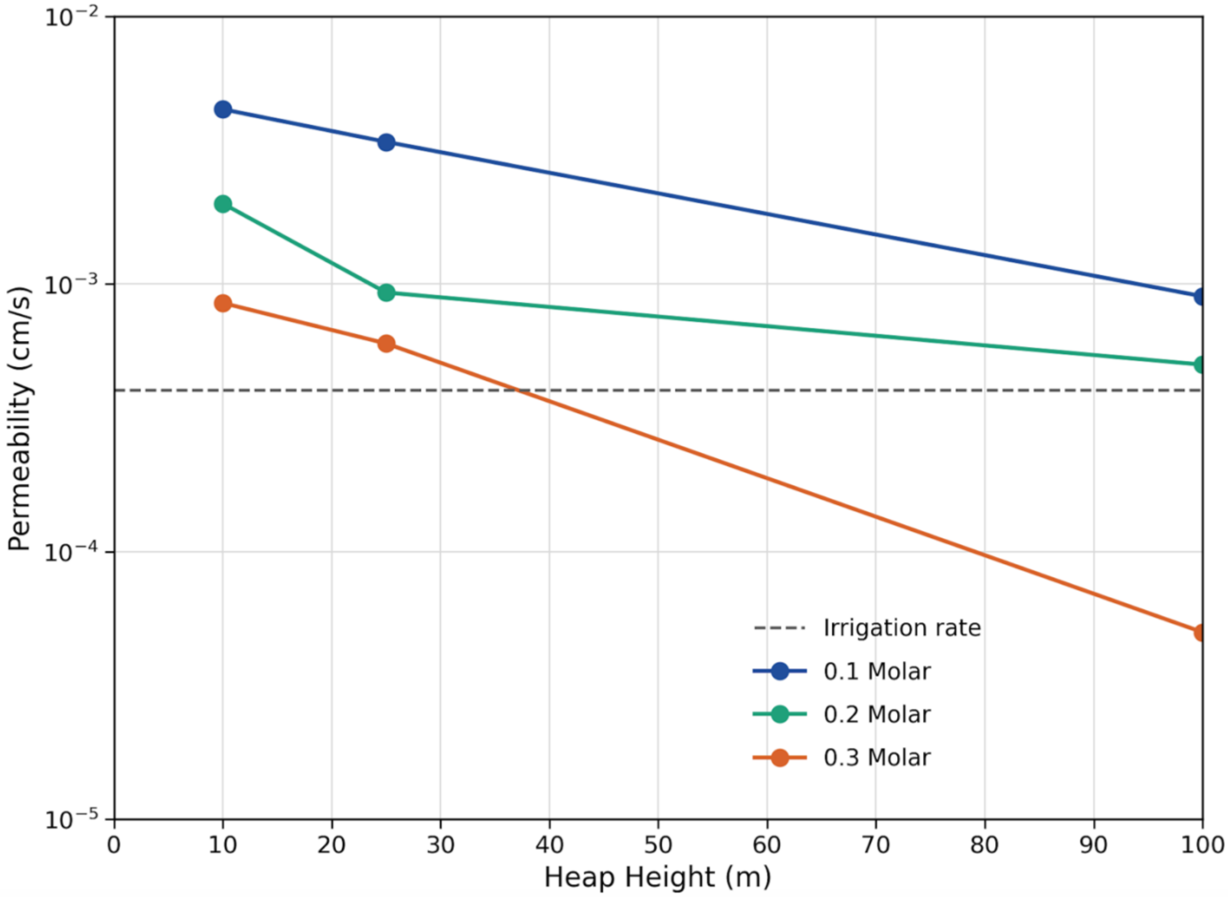

Figure 7: Permeability of leached copper ore versus depth in the heap for three acid concentrations at an HLF in Perú. The dashed line is the irrigation rate converted to cm/s

Static liquefaction has been observed in several large heap failures where low-permeability horizons created perched water tables or nearly saturated zones without phreatic development, along with excess pore pressure development (e.g., recent liquefaction failures in Chilean ripios dumps; Figure 5). Although quantitative frameworks for predicting undrained behaviour and liquefaction in heaps remain underdeveloped, recent failures underscore the critical need to explicitly consider undrained behaviour—and the coupling between irrigation, permeability and shear strength—in design acceptance criteria (Smith and Konrad 2025).

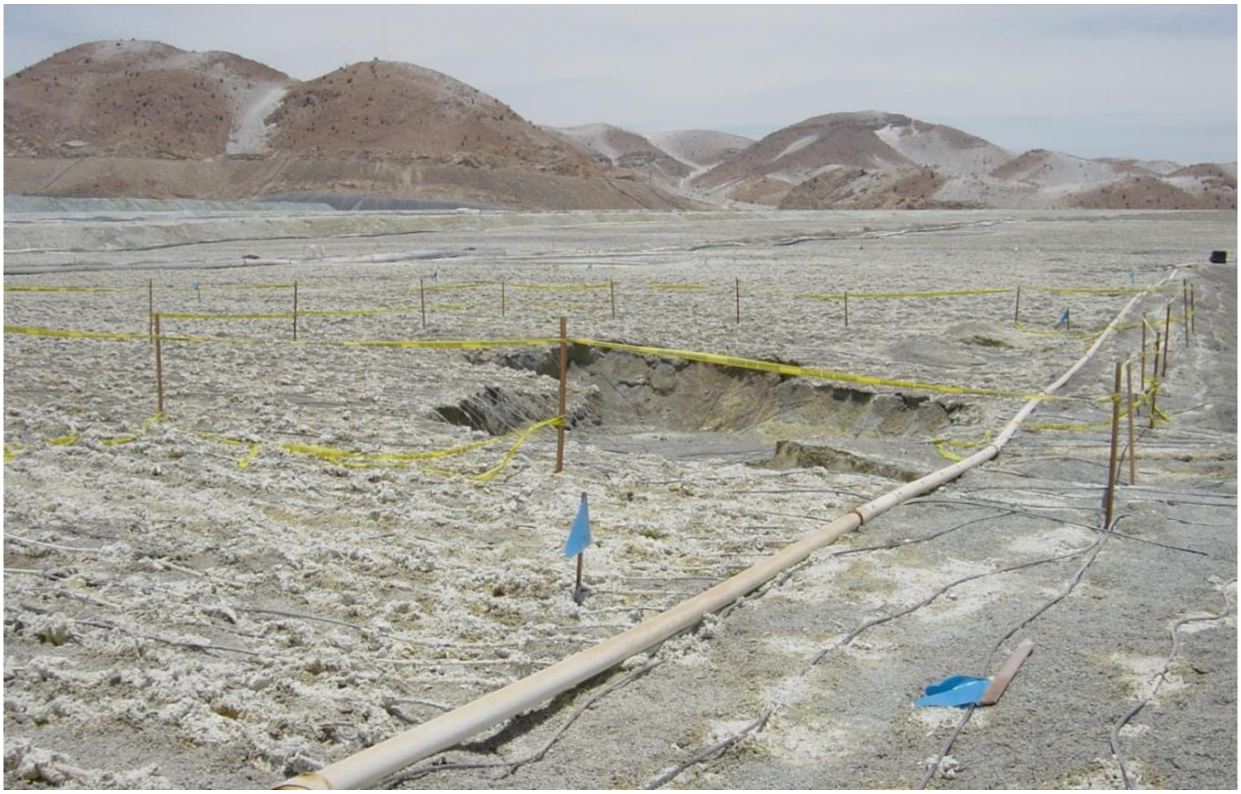

Figure 8: Sink hole in a copper heap in Perú caused by failure of a PLS collection header

Design and operational implications

Due to the critical nature of these geotechnical parameters, designers and operators should:

- Use conservative (lower) permeability values, especially for high clay ores, acid-leached ores or those likely to undergo physical or geochemical degradation in the heap.
- Monitor piezometric levels using vibrating wire piezometers (VWP) and, where practical, moisture content using soil tensiometers. VWPs can also measure matric suction (negative pore pressure), which can be correlated to the degree of saturation, though their reliable range for matric suction is limited to about 35 kPa for standard VWPs and 50 kPa for high air entry VWPs.
- Monitor permeability changes through field instrumentation and ongoing laboratory testing of the ore. While field instrumentation for permeability can provide valuable insight and become one of the critical controls, it is often impractical.
- Conduct cone penetration tests (CPT) with pore pressure measurements (CPTu) to collect good in situ data on a variety of properties, including direct measurement of permeability in saturated materials. When combined with a hydraulic profiling tool (HPT), higher quality permeability measurements can be taken, including in unsaturated layers. Both tools are highly recommended for use in crushed ore heap leaching and can have limited utility in ROM piles.
- Calibrate numerical models to actual field performance and adjust design assumptions accordingly.
- Assume initially higher permeabilities will degrade over the leach cycle, particularly in acid environments. For the Eagle Gold failure, the permeability of the lifts that controlled

the failure were two orders of magnitude lower than the values used in design (Smith and Konrad 2025).

- Confirm the overliner and drainage systems maintain at least one order of magnitude higher permeability than the ore.
- Verify the particle size distribution of the drainage gravel is compatible with the pipe perforation sizes (to avoid clogging) and spacing (to provide adequate pipe flow capacity) as well as the geomembrane (to avoid puncturing).

4 Heap and Dump Construction Fundamentals

4.1 Site Preparation

As with most infrastructure, successful HLF construction begins with rigorous site preparation. This usually starts with clearing and grubbing to remove organic and other unsuitable material that could compromise liner integrity or slope, and for many mines to salvage and stockpile soils for future reclamation. Earthwork requirements can be significant depending on the terrain and the type of leach pad selected. Subgrades must be graded to direct drainage towards collection systems and compacted to achieve uniform bearing capacity and minimise differential settlement. Where weak or compressible soils are present, remedial measures such as over-excavation, replacement or in situ ground improvement may be required. For sites with steep slopes, especially for VLFs, the grading design should also consider the required placement of anchor trenches for the liner system and construction access roads (Figure 9). Many, perhaps most, leach pads incorporate a low permeability layer beneath the geomembrane liner, which is typically a compact clay liner (CCL) or other low-permeability soil. Where geosynthetic clay liners (GCL) are used under the geomembrane liner rather than a CCL, the relatively low shear strength of both the GCL and its interface with other materials can increase grading requirements to maintain stable slopes. GCLs can also mobilise very low residual strengths (on the order of 5°), a risk often unrecognised during the design stage of a project and a hazard expressly included in the Heap and Dump Leach Pile Stability Rating and Hazard Classification System© (Smith et al. 2025).

In subarctic and alpine sites such as the high Andes and extreme latitudes, the presence of permafrost can complicate site preparation. Permafrost is generally classified as either thaw-stable (ice poor) or non-thaw stable (ice rich). In the latter case, the permafrost should be removed. For thaw-stable permafrost, the potential for creep under high loads should be investigated and considered in the design. This is not just a matter of whether the creep could create detrimental conditions, such as disrupting drainage or containment systems, but also whether the resulting deformation of the leach pad and heap can mobilise residual strength in strain-softening (also called strain-weakening) layers such as GCLs, GCL-geomembrane interfaces or strain-softening ores. For example, the GCL component of the liner system in the Eagle Gold VLF demonstrated a two- to three-fold reduction in shear strength when experiencing high strains (Smith and Konrad 2025).

Site preparation for leach facilities often includes subgrade drainage (underdrain) detection systems. Underdrains are used on sites with either shallow or perched groundwater, or sites subjected to seasonal spring activity. Underdrains are used to relieve hydraulic pressure beneath the liner system and contribute to minimising uplift gradients. These are often simple trenches filled with gravel and perforated pipes, ideally with non-woven geotextiles or filter fabrics to protect the gravel from clogging. More complex systems can include blankets of gravel or a herringbone system of small lateral pipes in gravel trenches feeding larger collection headers (essentially a mirror image of the PLS collection piping system installed on top of the liner). More sophisticated systems can include cutoff walls (which can be as simple as a shallow trench lined with a geomembrane or GCL and then filled with soil, or as complicated as a deep bentonite slurry wall) and interceptor wells to collect and remove shallow groundwater and thus suppress the water table within the leach pad footprint. Underdrain systems have the dual purpose of providing more separation between the liner system and any groundwater (and thus reducing contaminant transport) and avoiding uplift pressures on the liner system, which can create slope instability. However, it is no exaggeration to say that underdrain systems are the weakest link in many designs.

Figure 9: Geomembrane and GCL liner deployment on the steep west slope of the Eagle Gold VLF (reproduced from Smith and Konrad 2025 with permission)

Underdrains can also be used for leak detection, though they are not very reliable for estimating the location or size of any defects in the liner system. Engineered leak detection systems are sometimes used to estimate the leakage through the liner system. However, leak detection underneath single liner systems (a single geomembrane or a geomembrane/soil composite) are unreliable and generally used simply to comply with regulatory or licensing requirements. Their design tends to be simple pipe-and-gravel filled trenches but can also include more complex features such as lysimeters (to draw fluid samples from unsaturated zones), tensiometers (soil moisture meters) and VWPs (to measure pore pressure during both construction and operations).

The first lift of ore of most heaps that are stacked at the angle of repose and rest on a thin layer of drainage gravel over a relatively low-strength liner system will have a metastable slope with an FoS close to 1. Thus, the grading must be closely controlled, especially in the outer perimeter of the leach pad, to avoid creating local instability during and after ore stacking. This is also an issue for any HLF where the first lift of ore will be stacked in either the downhill direction or on-contour, as this exacerbates the first-lift stability issues (Smith and Giroud 2000).

4.2 Liner Systems

Liner systems are the cornerstone of leach solution containment. The conventional industry standard for large crushed-ore heap leach facilities is a single composite liner—typically a geomembrane such as high-density polyethylene (HDPE) or linear low-density polyethylene (LLDPE) placed over a compacted low-permeability soil layer, or occasionally a GCL). For high-risk facilities, particularly the in-heap pond portion of impounding VLFs, double composite liners with leak detection are the industry standard. The choice of liner system reflects both regulatory frameworks and site-specific risks such as slope stability and solution compatibility. The authors strongly encourage the use of single composite liner systems—a geomembrane in intimate contact with a compacted soil liner (such as a CCL)—for their superior performance compared to a single geomembrane over permeable subgrade.

Geomembrane selection is a critical aspect of liner design. HDPE remains the most widely used geomembrane globally due to its robustness, superior tensile strength, chemical resistance and relatively low cost. LLDPE geomembranes are the primary alternatives to HDPE and offer the advantages of higher multi-axial elongation and greater flexibility. In some jurisdictions, most notably Chile, single geomembrane liners without a composite low-permeability soil layer are the industry standard; a reflection of regulatory standards, the general absence of low permeability soils in the north of Chile and the depth (and even absence) of potable groundwater. This approach reduces costs and construction time, and it can also improve slope stability by omitting the weakest layer of the system. However, single geomembrane liners on permeable subgrade are significantly more likely to suffer large leakage losses, which poses both environmental problems and results in lost metal production. Therefore, for most installations the authors recommend composite liners over single geomembrane systems.

Compatibility with the chemistry of the leach solution is a matter of growing importance, particularly for facilities operating at low pH (e.g., copper and nickel laterite leach operations) and long exposure times. Research shows geomembrane performance can degrade over time through depletion of stabilising additives such as antioxidants. Abdelaal et al. (2012), for example, reported antioxidant depletion in both HDPE and LLDPE geomembranes when exposed to low pH solutions when an adequate antioxidant package was not included with the resin. This underscores the importance of matching geomembrane type and formulation to site-specific leach chemistry, as well as conducting accelerated aging and compatibility testing during design.

Long-term performance further depends on weld quality, placement practices, subgrade preparation and even the direction of placement of the overliner or first lift of the heap (Smith and Giroud 2000; Thiel and Giroud 2024). Even the most chemically resistant geomembrane can be compromised by poor installation or puncture from coarse subgrade material. Liner systems must therefore be designed to accommodate differential settlement, construction and stacking stresses and long-term loading without tearing, which emphasises the need for conservative geotechnical design, stringent construction quality assurance and long-term monitoring.

For cold climate operations, the behaviour of any exposed geomembranes, either temporarily or long term, should be considered. Some geomembranes are prone to loss of flexibility at cold temperatures, which can shorten the construction season. That said, the industry has good experience with installation temperatures as low as −15 °C. However, for all cold-weather installations, the owner and designer should consider any adverse effects of thermal expansion and design accordingly. Further, snow and ice can damage geomembranes if they are not adequately protected; this was a major contributor to the failure at the Summitville gold mine in

Colorado, USA, in the 1990s. Cold weather and wet ground conditions can also damage any GCL installed but not covered with at least overliner and, ideally, the first lift of ore. Covering the liner limits exposure to the coldest temperatures, and the weight over the GCL reduces swelling if the GCL is exposed to moisture, which can permanently reduce the available shear strength (this is often called prehydration). Damage to the GCL in areas where the overliner was not quickly placed was identified as the second-most likely cause of the Eagle Gold VLF failure. As a side note, bentonite hydration varies based on the water chemistry, and some leach solutions (very low or very high pH) will not fully hydrate the bentonite and thus the GCL may not be as effective as the designer assumed.

4.3 Overliner and Drainage Materials

Overliner systems protect the liner from mechanical damage during stacking and form the primary drainage layer to collect PLS. They are typically constructed of clean, durable gravel with a controlled particle-size range to prevent, or at least minimise, migration of fines while maintaining high permeability.

The overliner and drainage system provide the immediate interface between the ore and the liner system, and their proper design is fundamental to solution recovery, liner protection and heap stability. This layer serves several critical roles simultaneously: (1) it protects the geomembrane from puncture, (2) it provides a highly permeable drainage medium to efficiently carry PLS to collection pipes and ultimately the recovery plant and (3) it maintains long-term hydraulic performance despite chemical, mechanical and biological stresses, which then helps keep the heap well-drained and avoids high phreatic levels, which can be detrimental to slope stability.

Hydraulic conductivity of the overliner should remain at least an order of magnitude higher than the ore to provide consistent drainage over decades of operation. Pipe networks embedded in the overliner distribute flows to collection headers, and pipe perforation size and spacing must be matched to the gradation of the overliner. For example, if the overliner contains significant particles roughly equal to the width of the perforations, substantial clogging will occur, and the inflow capacity of the pipes will be impaired (Ghane et al. 2022; Smith and Konrad 2025). This is discussed in more detail in Section 4.3.4.

Long-term performance of drainage layers is a recurrent theme in case histories: once blinded or clogged, restoration is rarely possible. This makes careful design and construction critical. Overliner gravels and solution collection pipe networks form the critical line of defence in maintaining adequate heap drainage, yet their performance depends on appropriate gradation, physical durability and compatibility with the ore’s particle size distribution. The overliner gravel system can consist of either a single or double layer (Lupo 2010).

4.3.1 Material Selection

Overliner materials are generally selected to be coarse, clean and durable gravels with low fines content (typically ≤5% passing the #200 sieve) and chemically compatible with leach solutions. Angular crushed rock or screened alluvial gravels are both used, though in some cases lightweight synthetic drainage geocomposites (a combination of a synthetic drainage net, often called a geonet, and a geotextile fabric) have been employed as partial or supplemental drainage layers. For systems designed to support traffic, and especially the multiple loading and unloading cycles required with dynamic heaps, the traffic support capacity after saturation and fines migration from the ore can be the critical design criterion. If the ore is suitably strong and unreactive, screened ore is often the best overliner because its cost is offset by its metal value. For acid leach facilities, and especially for the very aggressive leach solutions used in nickel heap leaching, the geochemical durability of all materials should be verified, from overliner gravels to each component of the liner system.

For systems supporting truck and loader traffic, lateral stability under the heavy wheel loads while turning can be key. In some cases, especially with dynamic heaps, this can lead to the use of angular crushed stone. For gravel drainage layers, material gradation must balance high conductivity with filter compatibility; poorly graded or sand-rich gravels are prone to clogging caused by fines migration from the heap or clogging of the perforations in the drainage pipes. For a double layer system, the lowest lift is in contact with the liner and serves the primary purpose of protecting the geomembrane. The upper layer provides drainage and filtration against migrating fines from the heap. For single-layer systems, the overliner gravel serves all three functions. In both cases, the particle size distribution of the material encapsulating the drainage pipes must be compatible with the size of the perforations in the pipe, or clogging can occur (Ghane et al. 2022; Smith and Konrad 2025). Further, in both high and low pH systems, pipe and gravel clogging can occur due to chemical scaling (e.g., precipitation of sulfate and carbonaceous minerals). This is rarely addressed in the design stage but should be. High FoS for design flows (relative to system capacity) and redundant systems are the key to preventing long-term loss of performance.

4.3.2 Thickness and Placement

Typical overliner thicknesses range from < 0.2 m to > 1 m, depending on ore type, expected equipment traffic (especially for dynamic heaps) and site-specific design requirements. In years past, thin layers such as 0.3 m were in general use, but industry experience has demonstrated the rate and extent of damage to the geomembrane can be high for conventional placement and spreading systems. Evidence indicates the greatest risk to geomembrane integrity is during placement of the overliner, and this risk escalates rapidly for thin lifts. Thus, most systems now require the first layer placed be at least 0.6 m thick; for a two-layer system, the overall thickness will therefore approach 1 m. For ROM heaps, where individual ore fragments can exceed 0.5 m in size, thicker overliner layers are standard, sometimes > 1 m.

In addition to the overall minimum thickness, all drainage pipes should have adequate cover, where adequacy is determined by a complex interaction of drainage pipe type and diameter, gravel gradation (including not only the maximum particle size), angularity of the overliner gravel and design loading conditions. That is, the adequacy of the cover is not determined solely by its thickness. Most overliner gravel specifications call for top sizes of 35 to 50 mm, and some designers prefer about 20 mm. Note that “top size “can be defined as either the 100% passing size (P_{100}) or the 80% passing size (P_{80}). As used herein, top size refers to the P_{80}. Notably, laboratory testing for particle size distribution uses square sieves, and testing for performance, such as direct shear strength, permeability and geomembrane production, uses samples selected or created based on these square sieve tests. However, production screening plants nearly always use slotted screens. Thus, the production plant will need to use a finer slotted screen to reproduce the laboratory P_{80}.

4.3.3 Pipe Networks and Hydraulic Performance

Drainage networks consist of perforated collection pipes typically sloped towards headers and collection sumps or, in some cases, directly to the PLS pond. Pipe size, spacing and slot dimensions must match hydraulic loads and be compatible with the overliner gradation as discussed in the next section. Hydraulic conductivity of the overliner should remain at least one order of magnitude greater than the ore to maintain the preferential flow:

$$K_{overliner} \geqq 10 \times K_{ore} \tag{1}$$

where $K_{overliner}$ and K_{ore} are the saturated hydraulic conductivity (permeability) of the overliner gravel and leached ore, respectively.

Failures of poorly designed headers, widely spaced laterals or poorly connected pipes illustrate how inadequate drainage leads to perched water and the risk of instability (Figure 10). At the Eagle Gold mine, the increase in the phreatic level at each connection was estimated at up to 5 m due to a combination of the lack of a mechanical connection and use of a modest permeability (similar to that of the ore), sand-rich overliner gravel that clogged the perforations in the PLS collection headers. In the case of a large copper HLF in Perú, a combination of mechanical failures in the main collection headers, sandy overliner and chemically degraded ore led to the development of 11 sink holes in the crest, propagating vertically through up to 90 m of ore (Figure 8). When designing the overliner and the embedded drainage pipe system, it is important to keep in mind the overliner is collecting solution from an upslope area of the heap that is under leach.

4.3.4 Clogging and Fouling

Clogging of the perforations in the drainage pipe (Figure 11) is generally overlooked but can be a serious problem when the overliner has a high sand content. On the other hand, sand protects the geomembrane liner from puncturing and improves filtering of fines from the heap, reducing long-term clogging of the pores. Thus, one key to a well-designed and constructed overliner system is finding the optimum balance in the gradation of the drainage material, that is, a system that provides adequate protection of the geomembrane (some sand) while minimising clogging of the pipe perforations. Systems that are overly coarse put the geomembrane at risk, while those with too much sand can clog pipe perforations. Table 3 presents some commonly used criteria for both protection of the overliner from clogging with finer particles and to provide compatibility with the pipe perforations (Terzaghi et al. 1996). If the gradation of the overliner is such that perforation clogging is likely, pipe wrapped in filter cloth can be used to mitigate this problem.

Chemical scaling, such as gypsum, jarosite and iron hydroxides, fines migration and (less commonly) biological fouling can cause long-term performance loss. Figure 12 shows an alkaline carbonate uranium HLF in Namibia with surface ponding caused by a combination of chemical scaling and biological fouling. Poor agglomeration or segregation at the interface accelerates clogging. Robust filter design and conservative irrigation rates are the most effective preventive measures. Maintaining permeability over the decades-long operating life of an HLF is a persistent challenge. Chemical precipitation of gypsum, jarosite, iron hydroxides or other secondary minerals within the drainage layer is a recurrent issue, especially in acid leach systems (Figure 13).

Table 3: Common overliner gradation criteria

Condition	Criteria
Clogging of slotted pipe perforations by the overliner:	$D_{15(overliner)} \geq 1.0 \times$ slot width $D_{85(overliner)} \geq 1.5 \times$ slot width
Fines migration into the overliner from the ore:	$D_{15(overliner)} < 5.0 \times D_{85(ore)}$ $D_{15(overliner)} > 4.0 \times D_{15(ore)}$
Where $D_{15(xx)}$ is the particle size of material "xx" with 15% passing, and $D_{85(xx)}$ is the particle size of material "xx" with 85% passing.	

Figure 10: Lateral drainage pipes butted but not connected to drainage headers at the Eagle Gold HLF (reproduced from Smith and Konrad 2025 with permission)

On the other hand, biological growth (less prevalent in acidic systems) can contribute to clogging in neutral or alkaline operations. Biological clogging has been observed in the irrigation system of alkali uranium heap leach facilities and thus it is logical to infer that this could occur in the overliner system as well. Clogging of drainage materials by migrating fines is a persistent issue in heap leach facilities and should be considered in both design and operation. The risk is greater for dynamic heaps, where cyclic stacking and reclaiming prevent the heap and overliner from reaching hydraulic equilibrium. Overliner materials should be selected and maintained to withstand repeated traffic loads and to minimise loss of drainage capacity over successive stacking cycles. For all types of heaps, the selection of the overliner material gradation should be consistent with applicable filter criteria to minimise clogging by fines migration, such as that set forth by Karl Terzaghi (Resource Conservation Service 1994; Fannin 2025). The designers of dynamic heaps should consider removing 300 to 400 mm of the overliner on each cycle (along with the spent ore) as it is almost impossible to prevent fines migration into the overliner when the heap is being off-loaded. Removal of this sacrificial overliner layer takes some thought, as it should be done in such a manner that does not cause fines to migrate downward.

Figure 11: The PLS collection system for the Eagle Gold HLF showing high-sand content drainage material (reproduced from Smith and Konrad 2025 with permission)

4.3.5 Monitoring

The overliner is a logical location for embedding early warning instrumentation. VWPs placed just above the liner within the drainage layer can provide direct measurements of pore pressures at the base of the heap and provide direct indication of any problems with clogging or failure of the drainage pipes. Flow meters, weirs or flumes at the outlet of collection systems allow for rapid detection of changes in hydraulic performance, while sampling ports can be installed in select drains to monitor solution chemistry and detect scaling. See Section 7.5 for a discussion of more general monitoring systems including VWPs in the heap above the overliner system.

In summary, the overliner and drainage system represent some of the most important design elements of heap and dump leach facilities. They safeguard liner integrity, ensure reliable recovery of pregnant solutions and reduce the likelihood of pore pressure buildup and instability. Designs that balance filter compatibility, long-term chemical durability and redundancy in drainage networks consistently outperform minimal systems, providing both metallurgical and geotechnical resilience.

Figure 12: Chemical and biological fouling on a carbonate uranium HLF in Namibia

Figure 13: Partial chemical clogging of the overliner at a copper dynamic HLF in Chile

4.4 Ore Stacking

4.4.1 Retreat Stacking

In retreat stacking, the stacker operates on top of the leach pad for dynamic heaps and for the first lift of multi-lift heaps; the stacker moves on top of the prior lift for subsequent lift placement in the case of multi-lift heaps. The active stacking face advances while the stacker retreats (Figure 14). Retreat stacking remains the most used stacking method for crushed ores, reducing or eliminating equipment traffic on freshly stacked ore and the risk of reducing ore permeability and damaging agglomerates (Augusta Gold Corp. 2024; P2 Gold 2025). Conveyors and radial stacker systems dominate designs, with either portable (grasshopper-style) conveyors feeding a radial stacker (Figure 15) or shiftable conveyors feeding a tripper being the primary options (Cook and Kappes 2013; Fortuna Silver Mines Inc. 2023; Surimbayev et al. 2025). Retreat systems using radial stackers become impractical for high tonnage rate operations; as such, they are more prevalent in gold HLFs than copper HLFs. Talvivaara in Finland uses retreat bridge stackers to stack and then re-stack 40,000 t of ore per day. For many ores with even small amounts of clay, retreat stacking can create low- and irregular-permeability surfaces below the new lift being stacked. This can negatively affect heap performance, including creating perched water or higher degrees of saturation than desirable. For such ores, advance stacking with the stacker on top of the new lift is preferable, as the new ore is not wet or chemically degraded and therefore usually does not compact as much due to equipment movement as leached ore.

Figure 14: Retreat stacking of a dynamic heap with a shiftable conveyor and tripper in Finland. Modifications of this type of stacking system are also common for advance stacking

Figure 15: Retreat stacking with a radial stacker system in Central America

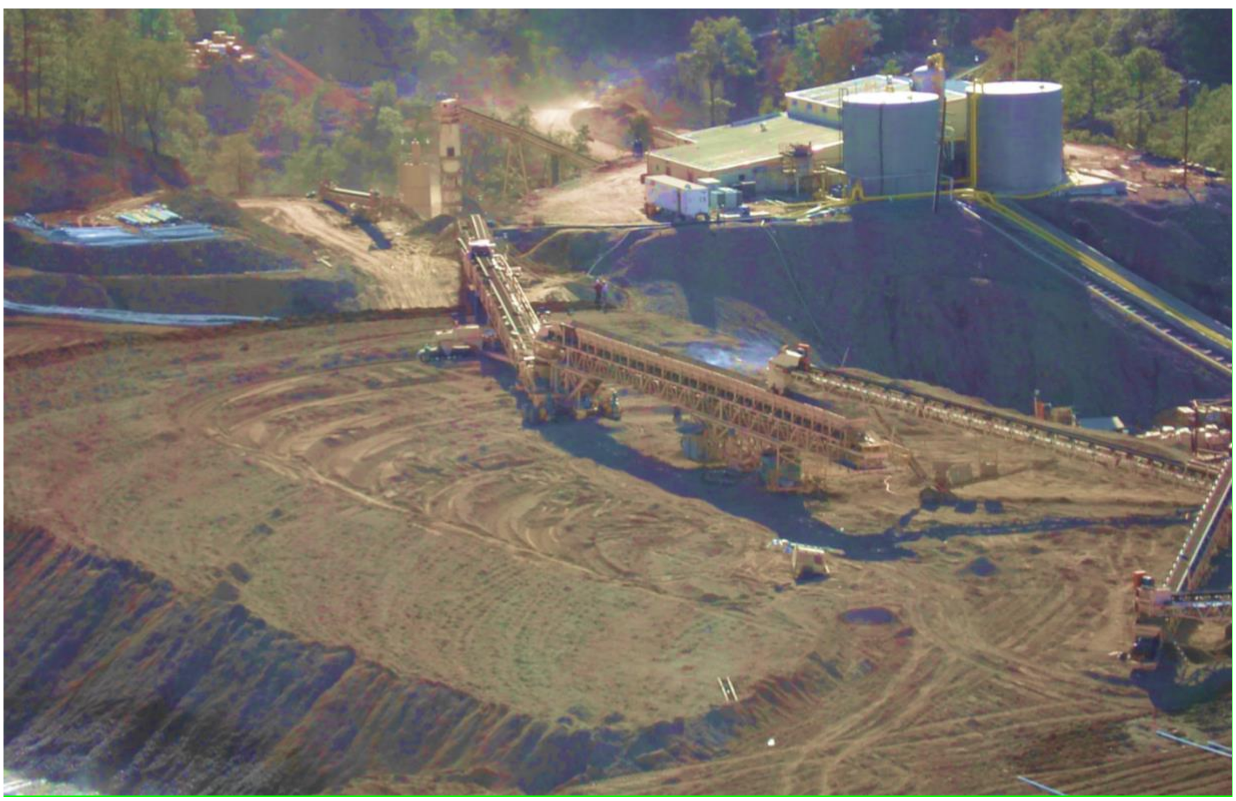

Figure 16: Advance stacking with grasshoppers feeding a radial stacker at a Mexican gold mine. Radial stackers can be used for either advance or retreat stacking

4.4.2 Advance Stacking

In advance stacking, the stacking equipment, haul trucks and bulldozers or a conveyor-fed stacking system operates on top of the lift being stacked. Conveyor-fed radial stackers (Figure 16) can also be operated for advanced stacking. Shiftable conveyors feeding a tripper is another way to advance stack and they are especially common for large copper dynamic heaps. Truck dumping, as shown in Figure 17, is the only practical option for ROM ore. Truck dumping is also used for other ores that are not impaired by truck traffic, especially those suited to leaching in relatively thick lifts. Advance stacking using either conveyors or trucks eliminates the lift height restriction imposed by retreat stackers and can offer significant economic advantages. The main advantage of using conveyor stacking systems rather than trucks is that they create a more homogeneous heap compared to haul truck stacking, which can result in alternating layers of higher and lower permeabilities.

Figure 17: Advance stacking with truck and dozer on a ROM heap

4.4.3 Race-Track Systems for Dynamic Heaps

Race-track designs are widely used for Chilean dynamic copper heaps, such as the El Abra, Radomiro Tomic, Gaby, Antucoyo, Centinela and Spence mines, and are an attractive option for dynamic heaps using bucket wheel excavators (Figure 18) for off-loading the ripios (Romo 2015). The leach pads are constructed as elongated, rectangular pads, usually with two leach pads side-by-side and a conveyor corridor between them. These leach pads are typically 200 to 500 m wide (twice that for the two-pad configuration) and tend to range from 800 to 1,600 m long (Figure 19). The conveyor corridor can then be used for both the feed (fresh ore) conveyor to the advance stacking system and the discharge or off-load ripios from a bucket wheel excavator (Figures 18 and 19).

Figure 18: Race-track system with bucket wheel excavator in northern Chile

4.4.4 Lift Thickness

Lift thickness directly affects both metallurgical efficiency and geotechnical stability, though the effects can vary significantly between ores based on maximum particle size, durability, moisture content, clay content and other factors.

Retreat stacking lift thickness is limited by the equipment, typically restricted to a maximum of about 10 m for both multi-lift and dynamic heaps (August Gold Corp. 2024; P2 Gold Inc. 2024; Surimbayev et al. 2025). Most dynamic heaps operate with lifts < 10 m thick to speed up the leach cycle, with 6 to 8 m being the typical range for gold and copper operations. Thinner lifts are generally used (e.g., 4.5 m at the Piauí nickel mine in Brazil and 4 m at the Ivan-Zar copper mine in Chile) for ores that significantly degrade under sulfuric acid leaching (most nickel laterites and many copper ores). Advance-stacked heaps, in contrast, can employ thicker lifts, sometimes exceeding 15 m, as there are fewer equipment restrictions. When the ore is transported to the heap via conveyors, it can be irrigated on the conveyor and thus stacked at a moisture content close to that required during the active leaching process. This can significantly shorten solution breakthrough times and therefore the leach cycle, as well as improve solution distribution throughout the lift.

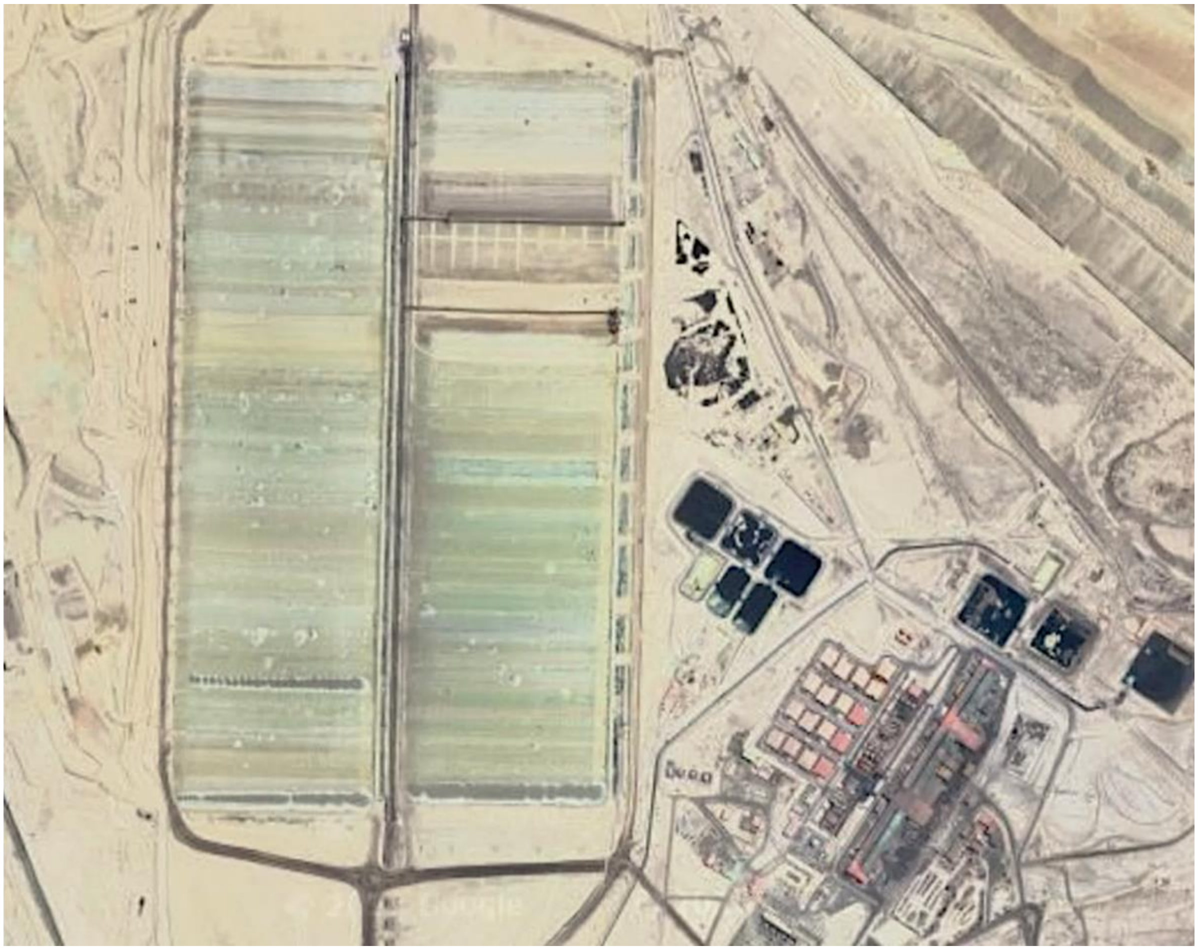

Figure 19: Radomiro Tomic race-track facility, northern Chile (Google Earth 2023)

In cold climates, thin lifts can exacerbate problems with frozen ore; once freezing develops in a heap, the frozen zones can be slow or impossible to thaw (Smith and Sinha 2015). Figure 20 shows the predicted temperatures in the Eagle Gold heap in 2023. Thick lifts can reduce heat loss during winter stacking and thus reduce freezing within the heap.

Thick lifts, especially with coarsely crushed ore, can promote particle size segregation with more coarse material at the base of each lift and more sand and fines in the upper portion of each lift; that said, this effect is highly dependent on the specific properties of the ore, including the as-stacked moisture content. Conversely, thin lifts can produce more uniform vertical permeability and reduce the risk of creating zones of high saturation and, in the extreme, perched water. However, thin lifts can produce larger differences between vertical and horizontal permeability, which in turn can promote abnormal solution distribution. Thin lifts are also slightly slower and more expensive to stack. The optimal lift thickness must therefore balance metallurgical kinetics, geotechnical stability, and operational practicalities. Good practice, when possible, such as with ore delivered to the heap via conveyor, is to moisten the ore with process solution to near operating levels (e.g., about 12% moisture on a dry weight basis for common gold ores). This accomplishes two things: fines stick to the coarse particles, thereby reducing the vertical segregation of coarse material and fines; and higher moisture contents result in lower capillary tension (suction), increased unsaturated permeability and process solution outflow that starts more quickly (reduced breakthrough time and shortened leach cycle).

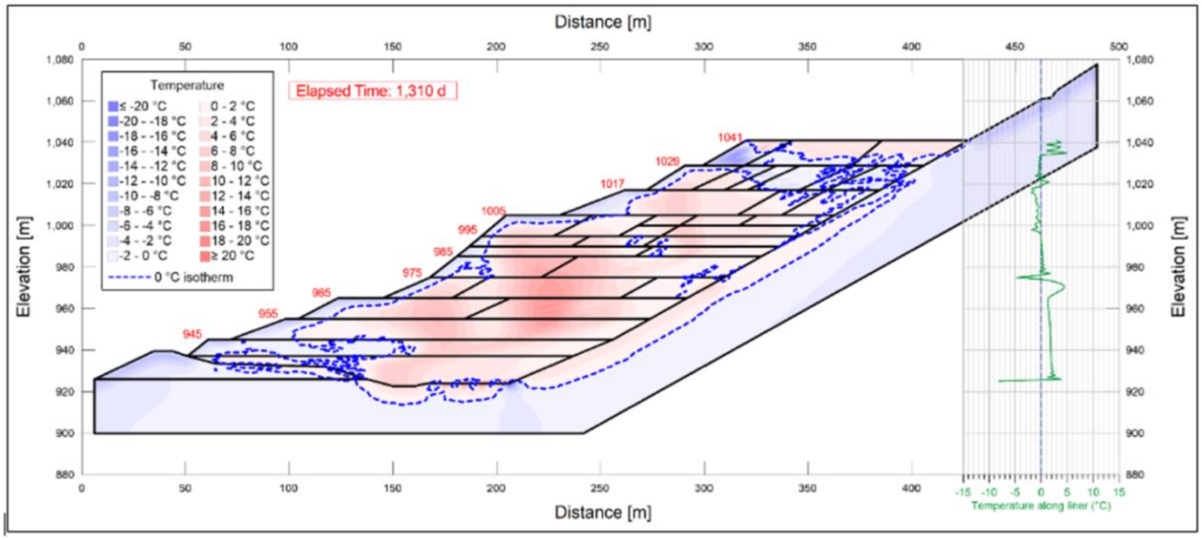

Figure 20: Patchwork freezing in the Eagle Gold heap predicted by modelling in April 2023 (reproduced from Smith and Konrad 2025 with permission)

5 Hydrogeologic Performance

Hydrogeologic performance is the bridge between irrigation practice and geotechnical behaviour of the heap, including saturation levels, the development of pore pressures and the mobilisation of undrained behaviour. As such, it is central to both metallurgical performance and geotechnical stability. Permeability dictates not only how solutions migrate but also how pore pressures evolve under irrigation. In practice, predicting in situ hydraulic conductivity is difficult: laboratory results rarely capture the full-scale effects of segregation, fines migration or chemical alteration over time. Unsaturated hydraulic conductivity (referred to as soil-water characterisation curves as shown in Figure 21), rarely characterised in detail, are especially important for forecasting solution distribution during early leaching or pulsed irrigation and are critical for evaluating the risk of mobilising undrained shear strengths; in the extreme, undrained behaviour can become liquefaction. Permeability is always affected by increasing overburden pressures – depth within a heap – as shown in Figure 22, but some ores respond more than others.

Solution application flow rates (typically expressed as average litres per hour per square metre, or L/h/m^2) and methods can strongly influence the internal flow regime. Irrigation systems, when well-managed, can provide uniform coverage and modest degrees of saturation (e.g. ±50%). However, when the irrigation rate is high relative to the permeability of the ore, the degree of saturation can increase significantly, often evidenced by side slope seepage and surface ponding. Some operations have found that for relatively low permeability ore ramping up irrigation rates from initially low levels (in some cases as low as 2 L/h/m^2) can improve the longer-term performance of the lift and the heap due to a variety of factors including more uniform wetting and avoiding the creation of preferential flow paths (Briseño et al. 2019; Robertson and Peterson 2025; Tancredi et al. 2025).

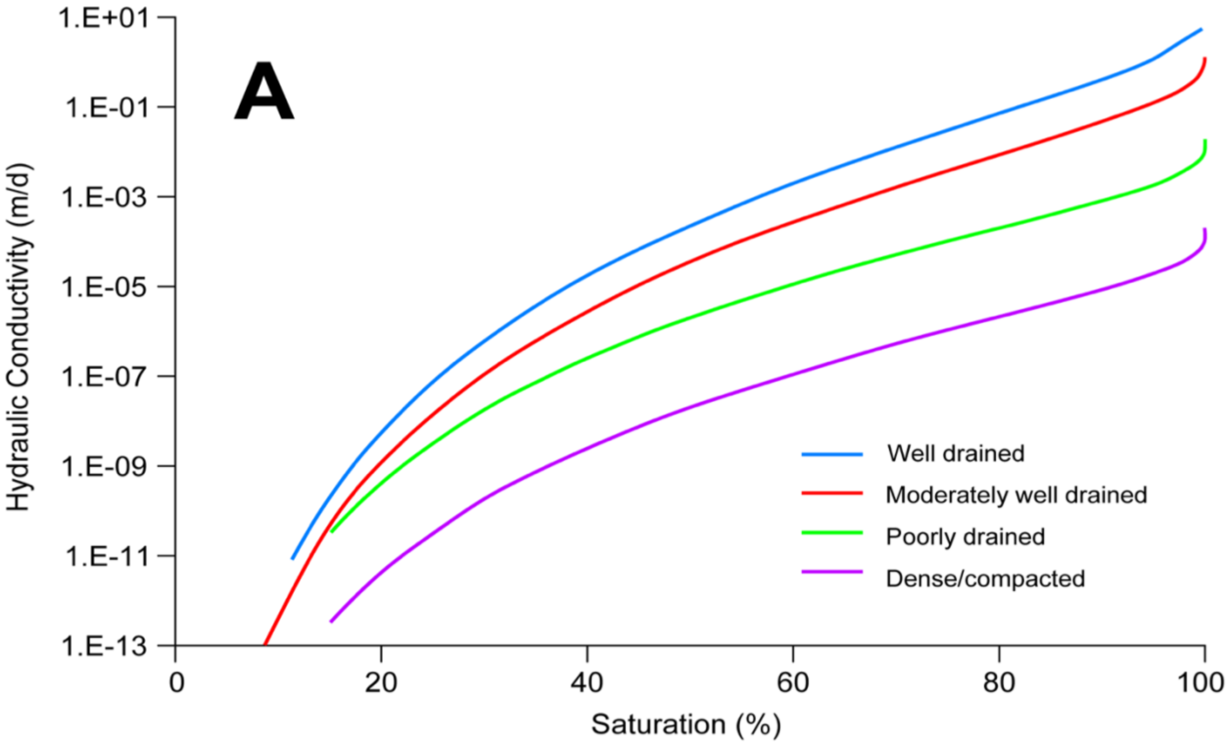

Figure 21: Unsaturated permeabilities from testing to establish the soil-water characterisation curves (SWCCs) for a variety of leach ores (after Rucker et al. 2015)

Most leach operations periodically irrigate the side slopes of the heap, as the metal contained therein can be a material percentage of the total. Figure 23 shows a view of the slope irrigation at Eagle Gold mine. However, side slope irrigation can also lead to slope failures if not well managed; this was identified as one of the key causes of the Eagle Gold failure as well as a number of less significant failures at other operations. Thus, many mines have specific protocols and geotechnical monitoring programs for slope irrigation that, ideally, are supported by stability analyses.

Hydrogeologic monitoring systems, VWPs, soil-moisture sensors and thermistors in cold climates are essential to track phreatic development and detect zones of high degrees of saturation and perched water. Integration of hydrogeological data into geotechnical models, as was done in the Eagle Gold forensic review, provides critical insight into failure triggers and helps calibrate design assumptions. Hydrogeologic properties should not be treated as secondary inputs; they are integral to both metallurgical recovery and slope stability.

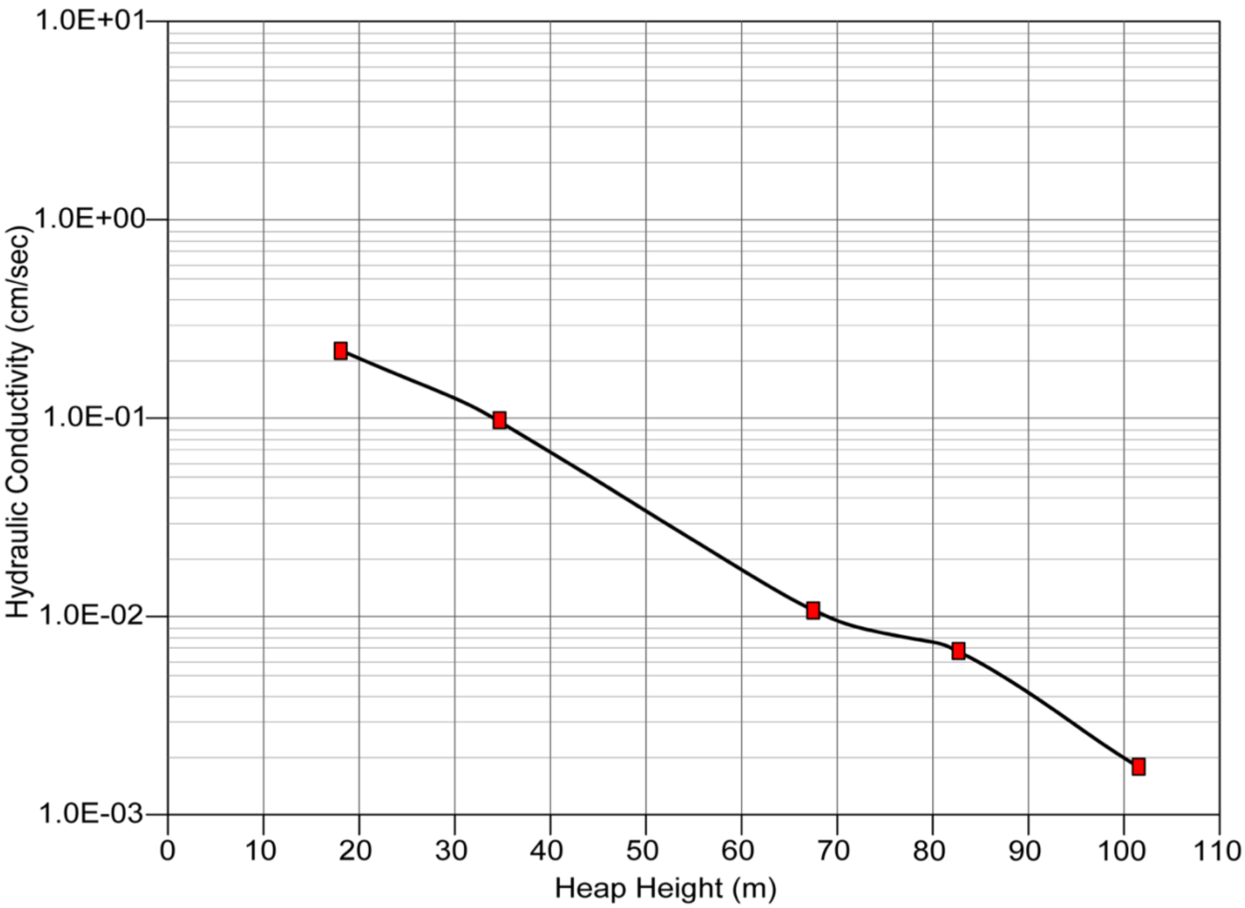

Figure 22: Saturated permeability vs depth in the heap for a leached copper sulfide ore in Chile

An often-overlooked detail is that PLS solution can have a relatively high specific gravity as compared to fresh water. This will affect the pore pressures in the heap in saturated zones and the interpretation of piezometric data. For gold and silver facilities this is a small correction, since the typical specific gravity of precious metal PLS is 1.01 to 1.02. For copper PLS the range is about 1.05 to 1.15 and values around 1.07 to 1.10 are common. Nickel laterite PLS has a much higher specific gravity and depends in part on the ore's content of acid soluble metals such as iron and magnesium. Typical ranges will be 1.13 to 1.18, but values > 1.20 should be considered for high acid, high dissolved solid operations.

Figure 23: Eagle Gold VLF showing slope irrigation in May 2024. Note the side slope seepage about 100 m vertically below the crest (reproduced from Smith and Konrad 2025 with permission).

6 Water Balance

Water balance management, as used in heap leaching, refers to the accounting of the amount of water in the system and where that water resides at any point in time. For example, water balance models are key in managing pond storage and predicting makeup water demand. A water balance model tracks all inflows, storage and outflows in an HLF, forming the basis for safe and efficient operation as well as improving the transition into closure. Key inflows include precipitation, makeup water, applied irrigation solutions—including recycled barren solution or intermediate leach solution (ILS) and water contained in the as-stacked ore. Storage comprises the solution held within the heap (dynamic storage), PLS collected in ponds and any water collected in stormwater structures (sometimes called event or emergency ponds). Outflows (including water consumption within the heap) include the water required to wet the ore, evaporation, leakage and occasional bleed streams. Ore water content is usually characterised using three parameters: moisture contained in the fresh ore stacked on the heap, moisture content while under irrigation and moisture content in the ore after irrigation has ceased.

In complex heap leach facilities, performing robust and precise water balance modelling can be extremely difficult given the number of variables. Water balances can vary widely from season to season and year to year. Stochastic simulations should be used as a routine tool to assess such variability; the industry should not rely solely on deterministic water balance models. Tools such as GoldSim (GoldSim Technology Group 2025) or METSIM (Lv et al. 2012) make it possible to obtain more information on evolving site conditions.

To be effective, models for facility design must account for both average and upset conditions. Critical inputs are climatic data (rainfall, evaporation, snowmelt), ore hydraulic properties, operational parameters (irrigation rates, recycle streams, leach cycle) and infrastructure capacities (ponds, pumps, diversion channels). Specialised software and spreadsheets are commonly used to simulate dynamic balances and test design storms, freshet events, or pumping failures.

During operations, water balance monitoring can help confirm the pond freeboard is maintained, pumping systems remain adequate and unintended discharge risks are minimised. At closure, models help design rinsing programs, predict long-term draindown and aid in designing any required covers and post-closure water management systems. Calibration to actual operating data is important, otherwise the models risk losing operational value. That said, this is a complex task and true “calibration” is often impractical. However, many operations have found water balance models that incorporate a combination of operational data, statistical analysis and trend analysis to be valuable tools.

Case histories such as those listed in Table 4 underscore the principle that a well-designed and continuously updated water balance is not optional but often critical to stable operations and safe closure.

Table 4: HLF failures due in part to inadequate water management

Mine Name and Location	Synopsis of the Issues
Summitville, Colorado, USA	Summitville was the site of one of the first large impounding gold VLFs (circa 1986). In 1994 it became a Superfund site. Inadequate water management contributed to unintended overflow and seepage from the VLF, though this was only part of the environmental problems.
Carson Hill, California, USA	In May 1989, this impounding VLF experienced an uncontrolled discharge from the facility into the adjacent New Malones Reservoir, an important drinking water supply for the city of Sacramento, California, USA. This was the culmination of several solution-management upsets. This mine closed after just 4 years of operation.
Hayden Hill, California, USA	The HLF faced significant stormwater challenges, especially during the 1992/93 near-record setting winter, resulting in multiple uncontrolled discharges and related community and regulatory issues.
Çöpler Gold Mine, Türkiye	While the failure has not been attributed directly to water management, it is clear from the many publicly available videos that excess water in the heap contributed to a saturated and unstable condition.
Eagle Gold, Yukon, Canada	The official report of the forensic investigation (Smith and Konrad 2025) identified poor solution management as one of the key causative factors. This site had a GoldSim-based water balance model, but it did not correlate with actual operating conditions in terms of either makeup water requirements or total solution volume in the ponds, which resulted in a number of pre-failure regulatory interventions and at least one lawsuit.

7 Operational Considerations

7.1 Ore Agglomeration

Agglomeration of crushed ore is a common practice that mainly aims to reduce or prevent percolation problems in the heap. Agglomeration also improves leach kinetics if the solvent (cyanide or acid) is added to the agglomerator and can improve the distribution of process reagents. Additionally, this initiates the metal extraction process during the agglomeration process itself. Agglomerated ore tends to be less prone to the segregation of fine and coarse particles during handling and stacking, which can create preferential flow paths and even blinded areas within a heap. As a result, agglomerated ore typically has better hydrogeologic properties than the same ore without agglomeration, though the benefits can be temporary (especially for acid leaching). Operators may often be tempted to use field experience to “optimise” the agglomeration process (such as by decreasing cement addition) to reduce costs, but this has led to many problems. For example, the Bellavista gold mine in Costa Rica processed lateritic ores, which had a very high cement demand, at a very high cost. Operators cut back the cement to produce agglomerates that visually met their qualitative criteria. However, this resulted in solution distribution problems and ponding on the heap. At the ill-fated Eagle Gold mine, the original design included ore type blending and cement agglomeration. During the licensing process, the owner eliminated mandatory ore blending and agglomeration based on permeability testing of just two composite samples. Inadequate management of ore variability was indicated in the forensic report as one of the two prime causes of the failure (Smith and Konrad 2025).

Agglomeration also typically reduces fines migration, and for cement agglomeration of gold and silver ores the cement can reduce the adverse effects of plastic clays. Figure 24 shows an agglomerator system for gold ore in Brazil. The crushed ore with added solution (generally barren or raffinate solution) is added to the agglomeration drum. For high pH leaching such as gold or silver, a binder like Portland cement is usually added to improve agglomerate strength and thus the hydraulic performance of the heap. The ore is then stacked in relatively thin lifts (typically less than 15 m thick), over a lined leach pad with an engineered pregnant solution collection system. Note that ore grade typically varies with particle size (often with the finest fractions having the highest grades), making it important to understand the grade distribution by particle size.

Figure 24: Agglomeration drum for gold ore at the Cuiú Cuiú gold mine in northern Brazil

7.2 Lift Sequencing and Size

Heap leach pads are nearly always constructed in phases, with the primary exception being on-off leach pads for dynamic heaps. To correctly size each phase of a leach pad's construction, one must first know the required minimum irrigation area according to the ore production plan, that is, the area required to meet the target metal production. The irrigation area is determined by the ore production rate, as-stacked density of the ore, the lift thickness and the primary leach cycle, with primary referring to irrigation before a subsequent lift is stacked. The simplified equation for the irrigation area is expressed as:

$$A = (P \times C) / (D \times L) \tag{2}$$

where A is the minimum irrigation area (excluding slopes) (m^2), P is the ore stacking rate (tonnes per day, tpd), C is the primary leach cycle (d), D is the as-stacked ore density (t/m^3), and L is the lift thickness (m).

The required leach pad area is the sum of irrigation area, area of the slopes of the pile or heap and perimeter area (to provide for setback from the toe of the heap to the edge of the pad, and any berms, collection ditches or pipeline corridors). For a typical 100-m-high multi-lift heap stacked at an overall slope of 2.5H:1V, the available irrigation area (not including the slope area itself) will be on the order of 25% of the leach pad area. The ratio of irrigation area to total pad area is much more favourable for a dynamic heap or the first lift of a multi-stack heap at 60 to 85%.

7.3 Irrigation Management

Drip irrigation is by far the dominant irrigation system used in heap leaching, and drip systems are well suited to reasonably uniform distribution of solution at relatively low flow rates (Figure 25). For complex geometry and occasionally for side slope irrigation, a variety of other systems are used, such as impact sprinklers (Figure 26). Large, high-flow impact sprinklers are also used to increase evaporation and thus reduce surplus water accumulation.

Typical application rates are in the range of 5 to 12 $L/h/m^2$. Dumps are usually irrigated in the lower range, as are ores with poor physical properties, such as some copper ores and all nickel laterites that can undergo geochemical degradation during leaching (Smith and Christie 2015; Smith 2022). Pulsed or variable rate irrigation is sometimes used to optimise reagent consumption relative to metal production, or to control moisture content within the heap. Pulse irrigation cycles can range from a few hours of irrigation per day to a few weeks per month. Some ores, typically those with marginally acceptable permeability, perform better when the irrigation rate starts low and then is ramped up over time. This is in part because the permeability of ore with a low degree of saturation (i.e., high matric suction) can be orders of magnitude lower than the saturated permeability, as shown in Figure 27.

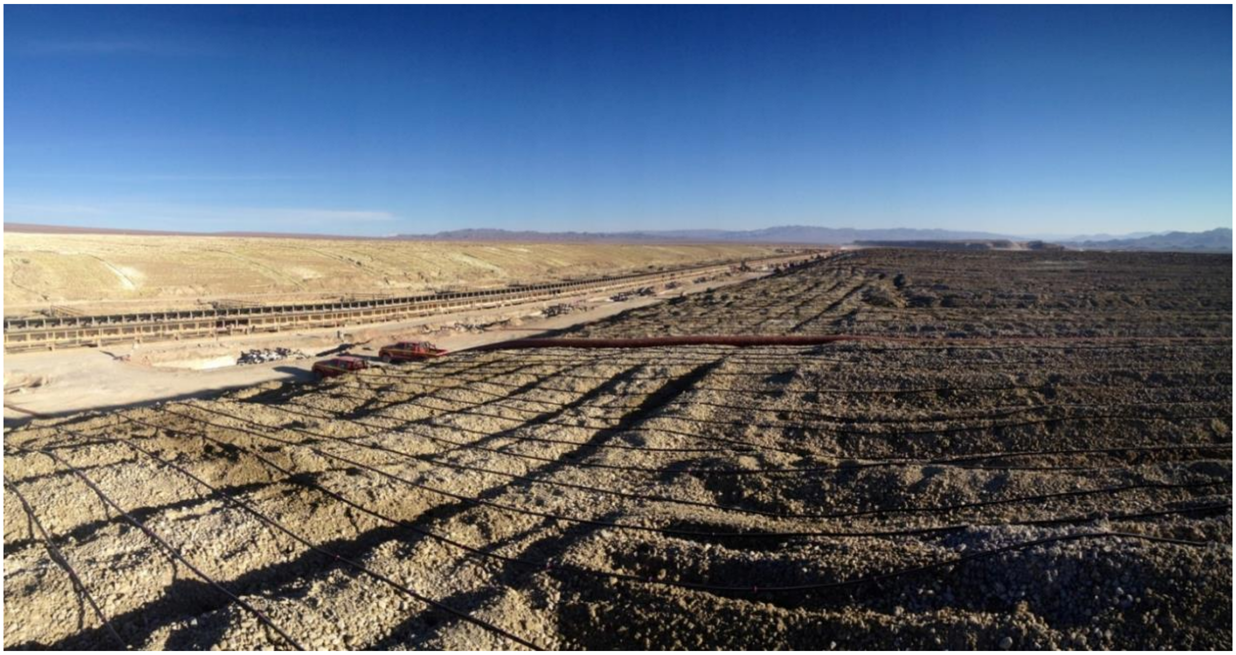

Figure 25: Drip irrigation system at a Chilean dynamic copper HLF

Figure 26: Impact sprinklers used in some dump leaching to increase evaporation

An increasing trend, especially in large and old heaps, is to use injection leaching for secondary recovery. When executed correctly, injection leaching can produce significant cash flow. However, if the geotechnical and hydrogeologic behaviour of the heap is not adequately considered, significant problems can ensue, up to and including slope failure (Shelbourn 2014). When injection leaching is contemplated, the owner should ensure a multidisciplinary approach with metallurgical, geotechnical and hydrogeological considerations receiving equal attention (Ulrich 2008). This should be coupled with a semi-quantitative risk assessment.

Slope irrigation can be a complex issue for large multi-lift HLFs. This is because the stability of the slopes is more sensitive to moisture content and degree of saturation in the ore within or adjacent to the slope than in the body of the heap. To highlight the criticality of proper control of slope irrigation, the Eagle Gold IRB report (Smith and Konrad 2025) identified heavy irrigation of the slope as the final trigger of the catastrophic liquefaction, as shown in Figure 28. The four lines of FoS represent these slope irrigation conditions: no irrigation, irrigation with optimistic ore permeability, and irrigation with the upper- and lower-bound permeabilities as determined by the IRB, respectively. The predicted date of the failure, as indicated by the FoS dropping below 1.0, corresponds to an ore permeability between the lower and upper bounds. Notably, slopes tend to start experiencing relatively large deformations at an FoS on the order of 1.1 (but this threshold varies widely based on material type).

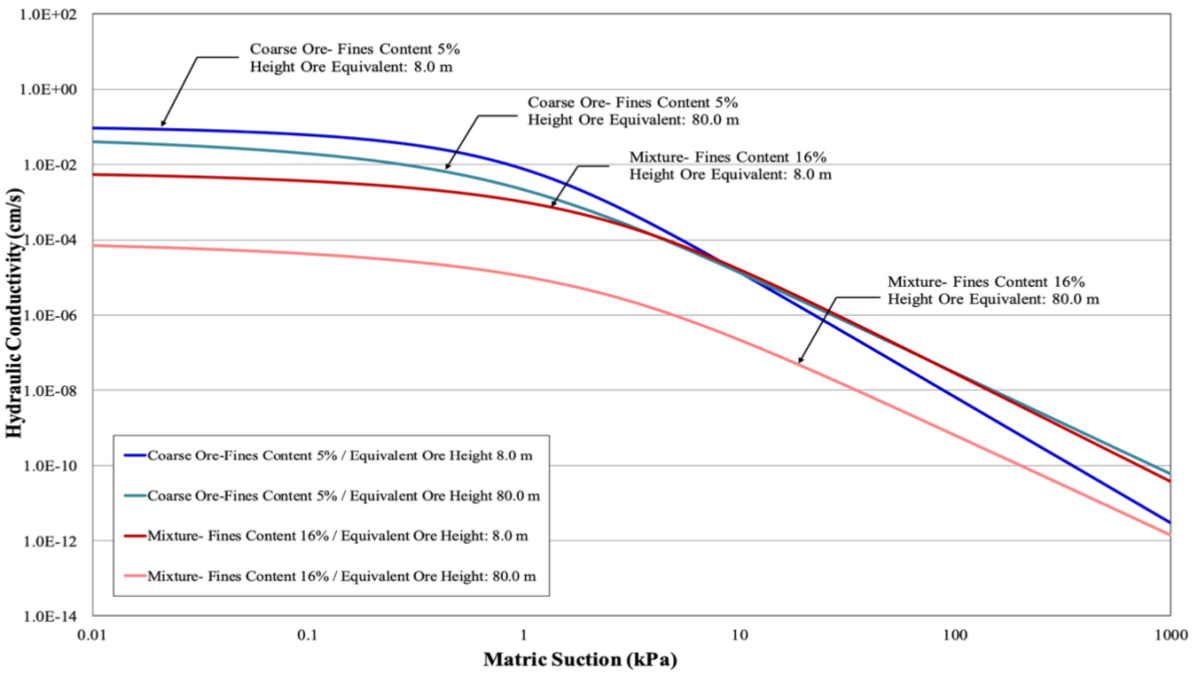

Figure 27: Hydraulic conductivity for a range of fines content and depths in the heap (reproduced from Chahua et al. 2016 with permission)

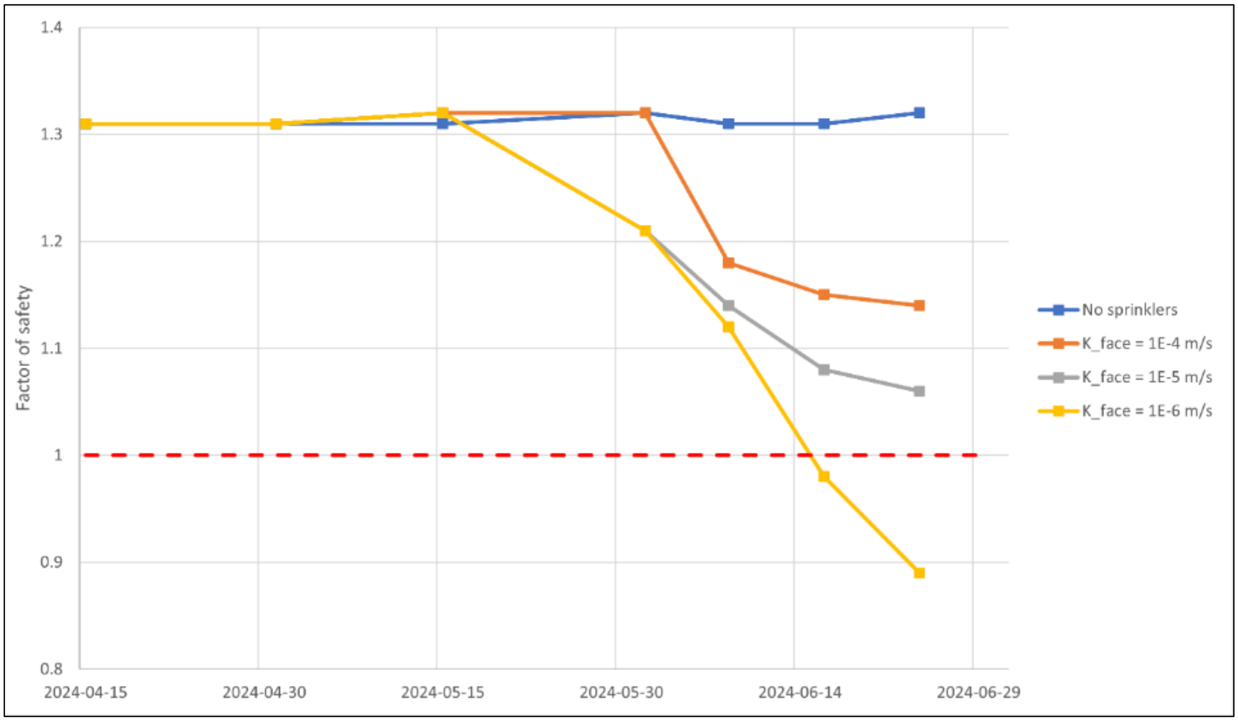

Figure 28: Eagle Gold factor of safety with heavy slope irrigation starting in mid-April 2024 (reproduced from Smith and Konrad 2025 with permission)

7.4 Aeration

Sulfide copper ores (e.g., chalcocite, covellite, chalcopyrite) require aeration during leaching because oxidation of sulfide minerals is driven by ferric iron (Fe^{3+}), which must be regenerated from ferrous iron (Fe^{2+}) in the presence of oxygen. Without adequate oxygen supply, leach kinetics slow significantly, solution chemistry destabilises and bacterial activity (in bioleaching systems, such as used for chalcopyrite and other primary sulfide ores) is suppressed. For example, the oxygen requirement to oxidise chalcocite (Cu_2S) is about 57% of that required for chalcopyrite ($CuFeS_2$). However, the oxygen requirement for both is such that an engineered aeration system is generally required to meet the oxygen demand (Liu and Granata 2018). Key requirements for bioleaching of primary copper ores include:

- **Air supply infrastructure:** Aeration is typically delivered through a network of perforated pipes embedded in the stacked ore, operating either passively (natural draft) or actively (forced air blowers). Forced aeration is generally required for chalcopyrite and other refractory sulfides.
- **Distribution and coverage:** Piping layouts must provide for uniform airflow; dead zones can quickly become anaerobic, leading to poor recoveries and excess acid consumption. This can require layers of aeration pipes at intervals (e.g., every few lifts). In gold heap leaches, oxygen (from air) is generally not required to leach the gold, but oxidising sulfides can cause reducing conditions that reprecipitate the gold within the heap (Marsden and House 2006).
- **Moisture control and temperature management:** Aeration must be coordinated with irrigation to prevent not just saturation but any level of saturation high enough to impede air flow. High degrees of saturation can create anaerobic zones, hindering bacterial oxidation. Bioleaching typically requires temperatures above 25 to 30°C; aeration

systems must be designed to sustain airflow even as the ore heats up from exothermic reactions. The elevated temperatures are generated by the biological activity, but without adequate aeration the exothermic reactions are suppressed, and the required temperatures may not be attainable.

- **Operational monitoring:** Aeration is monitored using temperature probes, solution redox potential (Eh), dissolved oxygen sensors and airflow meters to verify adequate oxygen transfer. Backup blowers and multiple air injection lines are needed to maintain continuous airflow, as interruptions can rapidly destabilise bacterial populations.
- **Case history evidence:** Evidence from the large bioleaching facility at the Escondida mine in Chile shows properly designed aeration systems, integrated with irrigation management, are essential for long-cycle sulfide leaching. They ensure sustained ferric regeneration, stable bioleaching activity and acceptable copper recoveries while minimising risks of pore pressure buildup and slope instability.

7.5 Monitoring and control

HLFs are complex systems that require custom-tailored surveillance systems, to attain optimum and safe performance. Performance monitoring systems used for geotechnical behaviour include (Julien et al. 2014):

- Ore testing on an ongoing basis to verify physical properties such as particle size distribution, permeability and shear strength
- Slope movement monitoring using survey prisms, ground-based LiDAR or RADAR, drone-based LiDAR and satellite surveillance such as offered by the InSAR system
- Pore pressure and phreatic level monitoring, which use a network of VWPs in the locations most critical to stability, at a range of elevations and in a variety of slope cross sections. Ideally, such systems include some VWPs either on the geomembrane or in the overliner layer.
- Moisture content monitoring using soil tensiometers to allow correlation to degree of saturation to detect zones with unacceptably high degrees of saturation (i.e., greater than about 80%)
- Periodic geophysical surveys (calibrated with piezometers, soil tensiometers, sonic drill holes and so forth) to identify zones of preferential flow paths, perched water tables and zones with high degrees of saturation. This work can also be used to evaluate the suitability for secondary recovery methods such as injection leaching.
- Visual monitoring for evidence of saturation or near-saturated conditions, including surface ponding and side-slope or bench-level seepage
- Temperature gauges (typically thermocouples) to monitor in situ temperatures for both bioleaching as well as any leaching in subarctic or alpine climates. The authors recommend the use of strings of thermistors with beads at uniform spacing.
- PLS collection system performance monitoring to verify the gravel overliner is compatible with the drainage pipes and, to the extent practical, that chemical scaling (especially for acid leach systems) is not impairing drainage, main collector pipes are intact (including, as appropriate, camera inspections), and the distribution of the flows from different sectors of the pad are as expected (thus checking for any unusual flow pattern within the heap).

- Water balance behaviour assessment, including pond levels, dynamic storage and drainage properties. This typically includes monitoring of barren, ILS and PLS flows, as well as ore moisture content (as stacked, under leach and drained). Flow rate measurements should use gauges reporting both instantaneous and total flow, with redundant flow meters used for critical flows (e.g., flow at the barren discharge from the ADR plant, makeup water flow added to the barren, and total flow to the irrigation system, which is a combination of the first two).

8 Environmental and Closure Fundamentals

8.1 Environmental Risks

8.1.1 Risks Common to All Leach Facilities

HLFs involve stacking large volumes of ore and irrigating them with chemical solutions to dissolve target metals. This approach creates several broad environmental risks. The foremost concern is solution management: any loss of containment through liner failure, overtopping of ponds or inadequate water balance control can result in contaminated releases to soil, groundwater or surface water. These solutions can contain constituents with both acute and chronic toxicity, cyanide, decomposition byproducts such as ammonia and other nitrogen compounds, mobilised heavy metals in the case of gold and silver, and sulfuric acid and mobilised metals for copper and nickel, all of which pose risks to human health, ecosystems and water supplies if uncontrolled. Another universal risk is slope instability; excess pore pressures, perched water or poor drainage can trigger slope failures, sometimes catastrophic, leading to both geotechnical and environmental consequences. Dust generation during stacking and closure, as well as residual leachate migration after operations, also require management.

8.1.2 Gold and Silver Leaching

Gold and silver ores are nearly always leached using alkaline cyanide solutions. Cyanide, while highly effective metallurgically, is acutely toxic to aquatic life and requires strict containment and detoxification measures. In some cases, the greater environmental risk as well as the chronic risks can be the other mobilised constituents rather than the cyanide. Risks include process solution spills, hydrogen cyanide gas emissions under low-pH conditions and long-term issues with residual constituents of concern in the ripios. Most silver and some gold-silver plants use the Merrill-Crowe process, which requires solution deoxygenation and zinc precipitation; poor process control can generate additional waste streams of zinc and other metals. From an environmental perspective, the challenge with gold and silver heap leaching is ensuring constituents of concern do not migrate off site, the facility has sufficient robustness and resilience to limit the consequences of any structural failure and closure programs effectively manage the leached residues.

To make matters even more complicated, many gold and silver ores have the long-term potential to generate acid rock drainage (ARD), despite the high-pH leaching process. The drive to rinse these heaps to some version of neutralised or detoxified can run counter to best management of long-term risks, in that leaving some of the alkalinity in the spent ore can help buffer longer-term ARD risks.

8.1.3 Copper Leaching

Copper heaps are irrigated with sulfuric acid solutions, and while the acid itself is hazardous, the larger long-term issue is ARD potential. Exposure of sulfide minerals during leaching or post-closure can generate acidic drainage that mobilises metals such as copper, zinc or arsenic. Laboratory and field tests show hydraulic conductivity can decline by orders of magnitude as ores degrade under acid leaching, creating perched solution zones and amplifying stability and seepage risks. Furthermore, most copper heaps operate at very large scales (hundreds of millions of tonnes), amplifying the consequences of any solution imbalance or containment failure. Unlike cyanide, sulfuric acid is not easily destroyed in the environment; rather, its risks are managed by designing for containment, neutralisation and long-term drainage control.

8.2 Closure Considerations

This subsection presents a high-level summary of closure specific to heap-leach facilities. The book *Guidelines for Open Pit and Waste Dump Closure* (de Graaf et al. 2025) also provides important guidance applicable to HLF closure. Further, the pending publication *Guidelines for Heap and Dump Leach Design and Operations* (Smith et al. in press) will include a chapter on heap and dump leach closure.

Successful HLF closures share a few consistent traits across case histories: they are planned early, driven by a defensible water balance and built around free-draining geometries that minimise residual saturation. By way of early planning, facilities that advance lifts to a near closure-ready slope and keep internal drainage paths open need less earthwork, simpler covers and will reach hydraulic equilibrium faster. Where operating for closure is ignored (e.g., irregular stacking, highly variable ore properties, perched water), regrading can be extensive and long draindown tails complicate water quality objectives.

Robust, site-specific water balance modelling is the second cornerstone. The best closure outcomes tend to pair conservative pond and pump sizing with seasonal and event-based scenarios (multi-week storms, rapid snowmelt, power outages), then practice inventory discipline during operations. Sites that underestimate infiltration, storm sequencing or pore water storage at rinse-down face overtopping risks, unplanned discharges and expensive emergency works. Modelling the transition from irrigation to closure (including the gap between declining application or irrigation rates and persistent PLS outflow, or the conversion of dynamic storage to pond storage or treat and discharge) is critical to avoid overwhelming pond and discharge capacity.

Cyanide detoxification and rinsing at gold and silver heap leach facilities are most effective when initiated while the heap remains free-draining. At subarctic or alpine sites, this includes ensuring the absence of any significant internal freezing. Solution recycle should be controlled to optimise rinse volumes throughout this phase. When detoxification is delayed or pond inventories are already under stress, closure targets take longer to achieve. These conditions also generate larger volumes of lower-quality water that must be managed over an extended period.

Sulfide copper leaching operations, and any heap carrying ARD risk, present a fundamentally different long-term drainage challenge. Acidic draindown should be anticipated over decades, not years, and closure infrastructure must be sized accordingly. This includes pump-back systems and lined conveyances designed for sustained operation. Neutralisation capacity should be determined with this extended timeframe in mind. Materials testing to characterise acid generation potential and permeability loss informs the selection of covers and drainage layers, with the goal of keeping phreatic surfaces low throughout the closure period.

Covers that match climate and residue behaviour generally perform better than one-size-fits-all approaches. In arid and high-elevation settings, coarse drainage layers under store-and-release (also called evapotranspiration) covers limit infiltration and preserve stability. In wet or freeze-thaw climates, composite covers with low-permeability cores reduce oxygen ingress and leachate generation but still require under-drains to prevent pressure buildup. A recurring lesson from experience is to keep the drainage system simple, accessible and inspectable; buried complexity hinders maintenance and early intervention.

Geotechnical verification matters as much as geochemistry. Closures that recheck shear strengths under closure moisture states, adapt operational design acceptance criteria (DAC) to the longer-term demand of closure (e.g., higher minimum slope stability factors of safety), verify liner interface parameters and instrument slopes (piezometers, survey prisms, drainage flow meters, thermistors where appropriate) will be more likely to sustain desirable performance. HLFs that close while still carrying elevated pore pressures or with fines-rich horizons will be more prone to slope movements and chronic drainage problems, prolonging active management, including water treatment.

Progressive or staggered closure consistently outperforms end-of-life campaigns. Further, progressive closure reduces the peak economic risks. Phased capping, early bench drains and step-down irrigation allow sections to stabilise and de-risk while mining and processing continues elsewhere. This staged approach creates learning and optimisation loops: monitoring data from the first cells refines rinse durations, cover details and water balance assumptions for later phases, shortening the overall path to compliance.

An early regulatory assumption in the USA, still reflected in some feasibility studies and licensing requirements, is that a heap must be rinsed at closure until effluent meets certain water quality thresholds (often receiving water quality). This is one closure option, but it is frequently either impractical to achieve or unnecessary. Such rinsing requirements can, in fact, create additional problems, including mobilisation of nitrates, sulfates, arsenic and antimony (Bowell et al. 2009). Parshley et al. (2012) demonstrated that rinsing beyond the residual metal recovery and inventory reduction phases is not generally required and can have deleterious geochemical effects. A more rational approach is a fit-for-purpose closure strategy supported by site-specific geochemical and hydrological modelling, such as that advanced by Miskolczi (2022) and SRK Consulting (2025). In a recent study for a large gold heap leach facility in Perú, this approach led to a closure strategy combining very limited rinsing, a modest closure cap to limit long-term meteoric water infiltration, and a passive collection and evaporation system for heap effluents. Similar approaches are underway in Nevada, USA, utilising infiltration basins or leach fields for effluent disposal. Finally, monitoring and contingency planning reduces closure surprises. Well-considered and verified trigger levels for pond inventories, slope movement, water levels within HLF, cyanide or acidity and downstream water quality, paired with preestablished response actions, can materially shorten incident durations and keep regulators and the site team aligned. Where closure plans embed long-term funding, clear ownership and simple operation and maintenance (O&M) routines, desired performance is more likely to persist. When closed correctly, heap and dump leach facilities are prime candidates to become stable and self-sustaining landforms after closure.

Further, a key closure consideration at many heap leach operations is the long-term condition of the containment system: should the liner system remain intact (to degrade with time)? Or are there benefits to be realised by breaching containment (e.g., perforating the liner to induce gradients)? As no human-constructed infrastructure, including liner systems, can last forever, there is merit in forcing the system into a long-term stable condition while the facility is under active management. This is especially important for impounding facilities such as pregnant and events ponds and impounding VLFs.

8.3 Operating for Closure

Optimum HLF management includes closure planning from the first lift of ore placed. Every operational decision—stacking direction, lift height, slope configuration, solution management and rinsing as part of metal recovery (where applicable)—has implications for how the facility can be closed. A well-conceived operating plan avoids creating features that complicate long-term drainage or cover placement and instead sets up a geometry and hydrologic condition that facilitate final chemical and physical stabilisation. For example, advancing lifts in a way that produces a stable overall geometry reduces the amount of regrading required at closure. Similarly, incorporating proper drainage benches and solution collection systems during active operations facilitates control of runoff from snowmelt or rainfall without degrading the slopes as well as efficient management of residual drainage.

From a leaching perspective, operating for closure also means balancing metallurgical recovery goals with long-term geotechnical and environmental performance. Aggressive irrigation or injection that produces perched water or saturated zones may boost short-term recovery but can create closure liabilities, such as high pore pressures that mobilise peak or even residual undrained strengths that persist into closure. Conversely, controlled application rates, systematic rinsing, and neutralisation strategies can reduce long-term risks by accelerating chemical stabilisation. Cement or lime addition (for gold and silver leaching) during agglomeration, for example, may slightly increase operating costs but can improve both structural integrity and long-term alkalinity, aiding in closure water quality as a buffer against ARD and metal leaching development.

Two case histories illustrate these principles. At Minsur's Pucamarca gold mine in Perú, the HLF was developed with a final closure geometry in mind, including regraded perimeter berms and well-drained surfaces that reduced the required quantity of closure earthworks, thus minimising retrofit costs due to irregular stacking geometries that complicated capping. Freeport-McMoRan's heap leach designs reflect a broader philosophy of promoting long-term stability, reliable drainage and efficient closure. This concept aligns with industry best practice: heaps should behave as free-draining, unsaturated structures, with elevated pore pressures treated as abnormal. By incorporating coarse, permeable zones within or around heaps—and in some cases wick drains—Freeport-McMoRan improves solution flow, reduces geotechnical risks and supports metallurgical recovery. This approach also simplifies closure by minimising residual saturation, easing cover placement and enhancing long-term stability. In practice, the free-draining shell designs represent an extension of Freeport-McMoRan's engineering culture, designing for both safe operations and sustainable closure outcomes.

9 Case Histories

The following abbreviated case histories serve as illustrative examples of the fundamentals of heap and dump leaching.

9.1 Escondida Copper Mine (Chile) – Sulfide ROM

Escondida (Antofagasta Region, owned by BHP and Rio Tinto) is the world's largest copper mining and mineral processing complex. In addition to a long history of traditional copper heap leaching, in the 1990s the owners and operators began investigating the leaching of primary sulfide ores including bio-oxidation to recover additional metal from lower-grade or reprocessed material. These programs focused on demonstrating biological oxidation for chalcopyrite/ secondary sulfide liberation and improving overall mass-balance economics while minimising water and reagent use in the Atacama arid environment (Gentina 2016).

Fast-forward to 2026, Escondida is home to the world's largest copper bioleaching facility, currently stacking 220,000 tpd of sulfide ore at this leach facility, and forecasting growth in the resulting copper production from 200,000 to over 400,000 tpa cathodes by 2035 (International Mining 2024; Wood Mackenzie 2024). Figure 29 presents a schematic of the operations. The leach pad is nominally 4,900 m long by 2,000 m wide, and the heap is to be stacked to between 126 and 160 m high. In addition, Escondida has a copper oxide HLF, which stacks about 48,000 tpd of oxide ore.

Key technical features are as follows:

- Bioleaching to enhance oxidation of refractory sulfide phases prior to SX/EW
- Using aeration piping to ensure adequate oxygen availability to satisfy the biological demand
- Process emphasis on maintaining aeration, temperature control and reagent dosing in low-water environments
- Bioleaching is viable for large sulfide resources when integrated with constrained water budgets and downstream SX/EW
- Noting rigorous pilot work and long-term monitoring are essential.

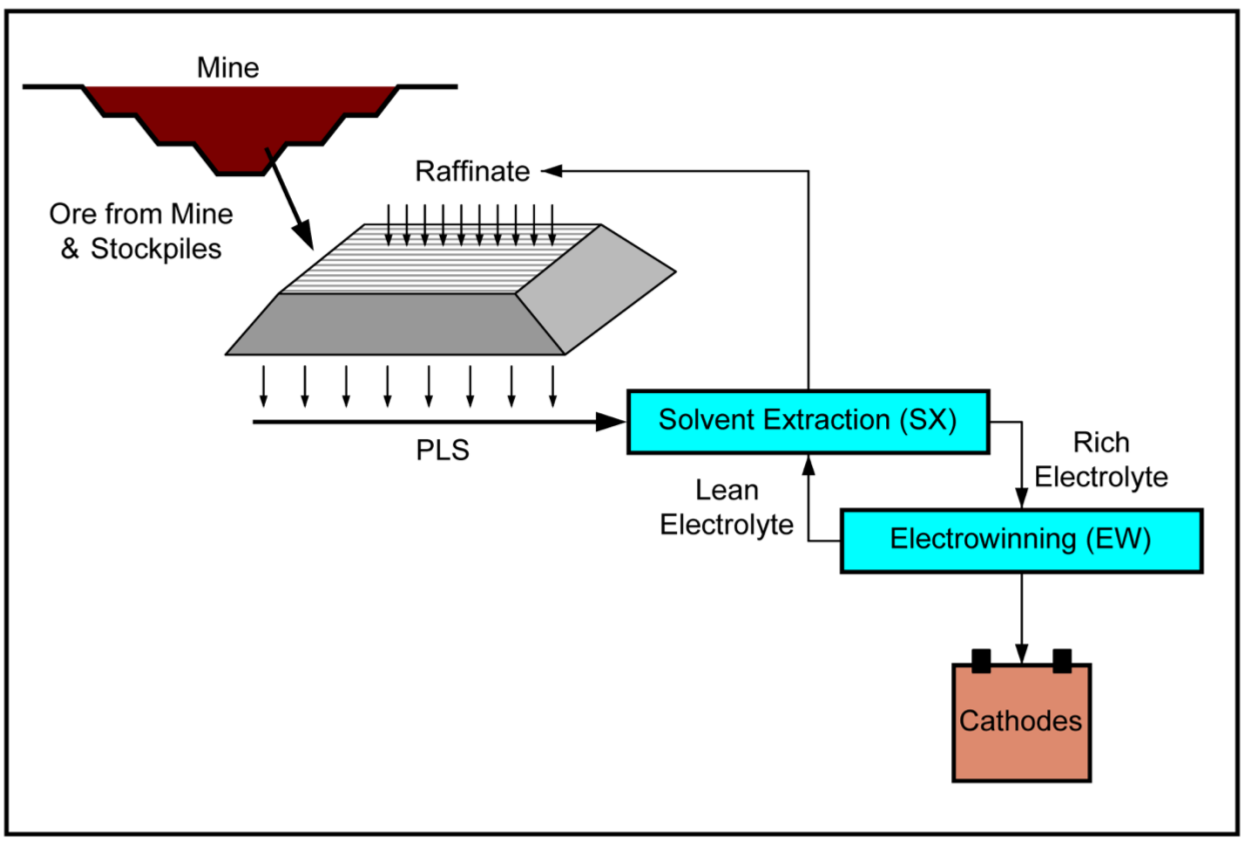

Figure 29: Escondida sulfide leach project flow schematic (after BHP 2004)

9.2 Pierina Gold Mine (Perú) – Impounding VLF

Pierina (Ancash, Perú, owned and operated by Barrick) is a high-altitude gold operation that historically used a single VLF as its only recovery facility. A longitudinal section of this facility is presented in Figure 30. The Pierina HLF was constructed in 1997 and 1998, with commissioning and first gold production in 1998. This was the first large, complex VLF to operate successfully. Mining concluded in 2013, and gold production continued for a few more years as the project transitioned into closure. The crest of the heap is at an elevation of about 4,290 m, approximately 300 m above the crest of the dam creating the in-heap pond. In recent years, Pierina has gone through progressive closure and is now in post-closure monitoring.

Key technical features are as follows:

- Ore production started at 19,000 tpd and ramped up to 27,000 tpd.
- Despite the complexity of this facility, with challenging geotechnical and climate conditions, the VLF was commissioned early, under budget and without significant problems.
- In its first full year of operation, Pierina was the lowest cash cost producer in the world, reportedly at $40/ounce.
- Ore blending protocols were developed and implemented to manage the minority of the orebody with low permeability, lower shear strength and vulnerability to developing undrained behaviour and thus earthquake-induced liquefaction. Pierina was the first heap leach facility to formally adopt ore blending specifications to manage the liquefaction risk.
- In 2009, the site performed pilot injection leach in 13 wells. This was expanded in 2012 and 2013 to a total of 133 wells developed to depths of 35 to 60 m. This triggered tension cracks in multiple benches and considerable slope movement. The slide was then stabilised with a staged cessation of the injection leaching program, offloading of some ore and construction of a buttress (Shelbourn 2014).
- The ultimate stacked tonnage was about 175 Mt with a designed maximum ore depth of 145 m, though the ultimate depth as stacked was about 120 m (Figure 31).

Several lessons have been learned, as follows:

- While there have been at least three important failures of impounding VLFs, and although they present a wide range of technical complications (Sinha et al. 2015), Pierina demonstrated that VLFs can be safely and profitably constructed and operated even in complex settings including high rainfall and strong seismicity. Large, complex VLFs are successfully operating at present in Alaska, with a planned second VLF at the Fort Knox mine (Mining Technology 2020), two VLFs in Argentina at the Veladero mine, and two in Colorado, USA, at the Cripple Creek and Victor Mine. Western Copper and Gold is preparing for licensing and construction of a new VLF at the Casino project in the Yukon, Canada (Casino Mining Corporation 2025).
- Injection leaching, to be successful, requires integration of geotechnical, hydrogeology and metallurgical disciplines (Seal et al. 2011; Breitenbach and Dolezal 2015).
- Closure planning should be integrated early and include multi-year chemical stability testing, robust water balance modelling for high-rain events and community-facing monitoring programs.

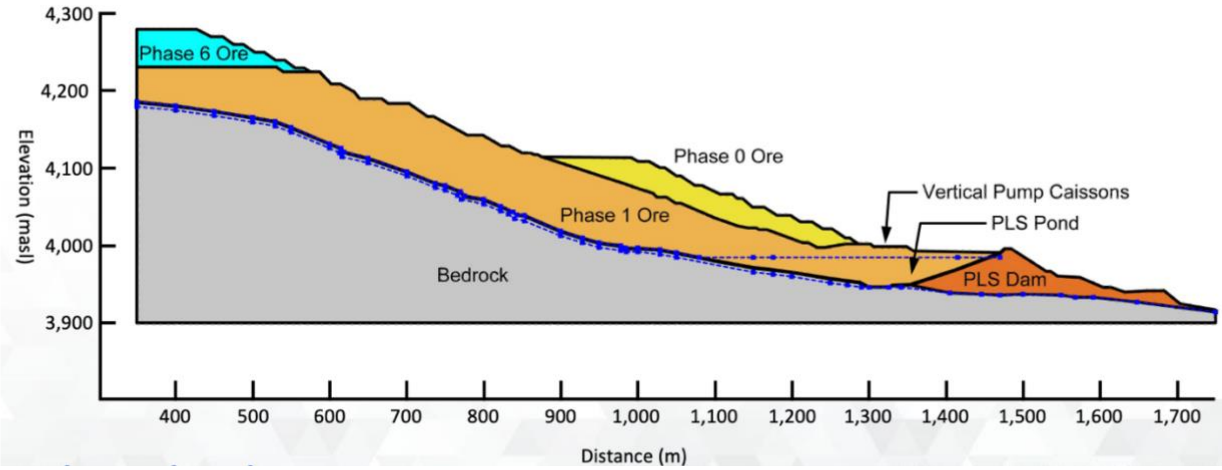

Figure 30: The Pierina gold VLF in 2014 (reproduced from Shelbourn 2014 with permission)

9.3 Marigold Gold Mine (Nevada, USA) – ROM

Marigold is a long-running ROM HLF in northern Nevada, USA, in production since the late 1980s. As of this writing, Marigold continues to operate and is planning an expansion project called Buffalo Valley. Its technical reports describe decades of operational experience: leach pads, irrigation strategies, carbon processing and iterative improvements in stacking, irrigation and solution recovery to sustain production through changing ore types. Marigold's public Canadian National Instrument (NI) 43-101 and technical summaries provide practical data about prolonged operations, evolving pad design and recovery (SSR 2018; SLR 2024).

Key technical features are as follows:

- A mature ROM HLF design with multiple pad phases and an established carbon processing circuit with a long and successful operating history
- Continuous adaptation of irrigation rates, stacking protocols and monitoring to manage variable ore permeability

Lessons learned are as follows:

- A long productive life depends on incremental process optimisation, continuous data-driven adjustments to irrigation and active inventory management of PLS and barren solution.
- Historical datasets from long-running operations are invaluable for scaling-up of new projects.

9.4 Piauí Nickel-Cobalt Mine (Brazil) – Dynamic Heap and Ripios Dump

Piauí (São João do Piauí, Brazil, owned and operated by Brazilian Nickel Ltd) is the first large commercial-scale nickel and cobalt HLF. This project started as a small-scale commercial leach facility (Figure 31), both as proof-of-concept and to produce nickel and cobalt intermediates (often called mixed hydroxide precipitates or MHP), with the first nickel produced in the second quarter of 2022. The next stage will be a large expansion with a production target of 3 million tpa of laterite ore to produce 25,000 tpa of nickel equivalent as a mixed hydroxide precipitate. Nickel laterites have much higher acid demand (typically about 10 times) than copper leach ores, and thus they operate at much higher acid concentrations (and very low pH) in the raffinate. The leach kinetics are also relatively slow, with a leach cycle of about 14 months for a 4.5 m high lift.

Key technical features are as follows:

- Relatively strong acid and laterite ores result in about 20% of the stacked ore being dissolved during the leaching, leading to significant changes to the geotechnical properties.
- The high silica content of the typical Piauí ore results in a relatively competent matrix and reasonably good hydraulic performance in the heap.
- The 20% dissolved weight is nearly all impurities such as iron and magnesium compounds, which must be removed through a series of chemical precipitation and filtration steps in downstream processing. This results in the production of plant residues that are then co-disposed with the leached ore. This combined ripios and plant residue dump is the key geotechnical feature of this facility.

Figure 31: The Piauí dynamic nickel heap leach facility in Brazil (source: Brazilian Nickel Ltd, used with permission)

9.5 Freeport-Mcmoran Copper Complex (Arizona, USA) – Heap and Dump Leach Facilities

Freeport-McMoRan operates several open-pit, leach-based copper facilities in Arizona that utilise ROM and crushed ore leaching coupled with SX/EW processing.

Key sites include:

- Safford (including Lone Star): An oxide leach operation where crushed ore from the open pits is conveyed to leach pads, with a downstream SX/EW facility designed for producing cathode copper.
- Bagdad Mine: Includes stockpile leaching and pressure leaching circuits feeding an SX/EW plant. Reserves feature leachable oxide and sulfide mineralisation.
- Chino and Morenci Mines: Both utilise a combination of ROM dump leaching and traditional concentration. Leach piles feed large-scale SX/EW plants. Morenci, especially, under the “Leach to the Last Drop” initiative, is extending copper recovery from existing stockpiles.

Innovations and expansion plans include the following:

- Geothermal-enhanced leaching: Freeport is pioneering thermal enhancement in Arizona leaching operations. It has partnered with the US Department of Energy for a geothermal heating project at Morenci and Safford, aiming to boost secondary recovery of residual copper from previously uneconomical stockpiles and reduce emissions and energy use.
- Sulfide leaching: At Morenci, sulfide leach production is now over 100,000 tpa of copper cathode, with a target to reach 400,000 tpa by 2030, comparable to the output of a major new mine (Freeport-McMoRan 2024).

These operations focus on integrating geotechnical management of heap and dump leach facilities with metallurgical innovation, particularly in managing water, heat flow, ore permeability and metal recovery over the long term.

10 Summary and Key Takeaways

In summary, HLFs are mineral extraction facilities with many parallels to traditional milling. As such, they can and should be designed to achieve a target percentage of metal recovery in a target leach period. They are much harder to manage than an agitated leach plant or a copper concentrator. This is because conclusive data are available within a few days of the ore entering the plant, but this is not the case for HLFs as such data are not available for several months or, in the case of some copper ores and all nickel laterites, a year or more. It therefore requires much more discipline to construct a heap leach that will perform as the design says it should, but there is no reason why it cannot be accomplished.

To compound those design issues, HLFs are governed as much by geotechnical and hydrological behaviour as by metallurgy, though most projects are primarily driven by the metallurgy. Ore type, ore preparation, ore stacking methods and solution management all exert strong influences on both recovery and stability. History has taught the authors that the most successful projects have taken multi-disciplinary approaches with similar weighting of those three disciplines. All failures can be attributed, at least in part, to inadequate consideration of at least one of these three; the Eagle Gold and Çöpler catastrophic heap leach failures are excellent examples of this.

Case studies from operations in Chile, Perú, Argentina, and the USA demonstrate that oxide and sulfate ores typically yield higher and faster recoveries, while secondary and primary sulfides require long cycles, elevated temperatures and—especially for primary sulfide ores—bacterial catalysis to achieve meaningful results. ROM leaching offers economic benefits through low cost and broader ore utilisation and can demonstrate better geotechnical behaviour, but generally lower recoveries and greater variability. Agglomeration, careful irrigation design and proper ore blending or sorting strategies can mitigate many of the risks of fines migration, channelling and pore pressure buildup. Ultimately, successful projects balance metallurgical efficiency with sound geotechnical design and adaptive management, supporting not only economic viability but also long-term stability and environmental performance.

11 Acknowledgements

The authors thank Anne Oxley of Brazilian Nickel Ltd, Michel Julien of Agnico-Eagle Mines Ltd and Erin Dowd of the Yukon Department of Energy, Mines and Resources for their important technical and editorial contributions during the preparation of this paper.

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