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Geotechnical engineering for heap leach operators

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Abstract

The authors present a geotechnical primer especially oriented to heap leach operators, as well as geotechnical engineers new to heap leaching. The geotechnical behavior of leach heaps and pads can have important impacts on a wide range of key issues, from leach kinetics to environmental and safety risks. The failure to properly predict, incorporate, or react to changed conditions has led to a long list of serious problems: dramatic capital and operating cost overruns, inability to achieve economically viable extraction rates, physical instability of the heap and the related risk to the environmental and human health or safety, excessive leakage through the liner system and the resulting environmental risks and legacy issues, as well as regulatory violations being a few of those. Four key stages of projects are addressed: design and construction, commissioning, operations, and closure. For each stage certain weaknesses or gaps in the geotechnical data collection and analyses tend to reoccur from project to project. This paper will address these deficiencies, giving real-world examples, and provide some operational guidance for recognizing these issues and best using geotechnical resources to avoid negative consequences.

Introduction

Traditionally applied to gold and copper, heap leaching is also being applied commercially to uranium (e.g. in Imouraren, Niger and Trekkopje, Namibia) and nickel ores (Murrin Murrin, Australia, Yuanjiang, China and Piauí, Brasil) (Smith and Oxley, 2014). Over time, the limits on project sizes have expanded. Leach pads as large as 2 km^2 and piles as high as 140 m are becoming common, and substantially larger projects are in operation – Escondida Sulfide pad in Chile is almost 10 km^2. Along with such advances, the geotechnical implications and the risks of failure have increased. This paper highlights some of the geotechnical challenges that can arise at various stages of the project and offers some examples of where integration of geotechnical and process engineering can be critical. The authors have grouped these into four typical phases of a project: design and construction, commissioning, operations and closure. There is, of course, considerable overlap between these.

Design and construction

Silo effect

This term refers to a culture that induces a lack of communication and cross-departmental sharing of information amongst people involved in the same project. In heap leaching – a metallurgical process by nature – the geotechnical issues are often viewed as adjunct and the involvement of the geotechnical team is limited in scope. It is not uncommon to develop an overall concept of a heap leach facility before engaging geotechnical experts in any significant capacity, and then limit their scope to simply working out various details. Once the operation is commissioned, the geotechnical engineers are often involved only in connection with pad expansions or when problems arise.

Such compartmentalization is a logical result of the increasing size and complexity of projects and emerges from the practical requirements of project delivery. In reality, heap leaching is a fully coupled geotechnical-hydrometallurgical process and successful development requires some coupling of the various disciplines. An uncoupled approach can preclude a full understanding of the geotechnical issues. On the other hand, key decisions related to heap height, stacking method and sequence, and irrigation rates remain locked in without due consideration of the interactions between hydrometallurgy and geotechnical behavior.

A prime example of this is an existing heap leaching facility with chronic drainage problems arising due to leachate collection header failures and reduced permeability of the leach pile. The leachate collection header damage could have happened during construction and the reduced permeability was the result of a combination of chemical degradation of the ore under the leaching environment and increasing load as the pile height increased. Together, these caused excessive hydraulic head buildup over the base liner. The result was a slope failure, extended cessation of leaching, and extensive remediation work. From the process engineer's perspective, reduced permeability impacts the leaching rate and cycle, but to a geotechnical engineer it suggests pore pressure build-up and potential structural failure. Interdisciplinary engagement and the alignment of the two perspectives at an earlier stage might have prompted additional testing and analysis and an across-the-board improved understanding of the implications, possibly resulting in design, construction and operational alternatives such as: larger pad with lower pile height, inter-lift liners, a dynamic heap, reduced solution application rates (lower irrigation rate or pulse irrigation), or internal drainage structures.

Improper ore characterization

Just as the variations in ore grade, reagent consumption, grinding or crushing indices affect productivity factors, the natural variability of geotechnical properties also affects drainage and stability of the heap and, therefore, production and profitability. The most common approach to geotechnical characterization of the ore is to consider ore body average or typical properties. However, if the variation is significant the notion of typical becomes meaningless. In such cases a better approach is to characterize each of the major types of ore (Caceres, 2013). If all of the ore types are well behaved from a geotechnical perspective, then the heap can be designed using the lower-bound parameters. But if some of the ore types are problematic, then a different approach is needed. First, the heap behavior should be analyzed based on an accurate representation of stacking of each of those ore types. This, in turn, requires a coupling of the heap stacking and mining plans. If this results in problematic performance, such as a weak ore being placed in a critical slope area, then the alternative is often to blend ore types to produce acceptable geotechnical properties.

The latter approach was used in a gold mine in South America which had five major ore types. Three of these (e.g. types 1, 2 and 3) had excellent strength and percolation; type 4 had acceptable but marginal strength and percolation; type 5 had moderate strength and poor percolation. Based on these classifications, a further testing and acceptance protocol was developed which required: i) an intensified level of control when type 4 or 5 ore was being mined; and ii) blending type 5 ore with types 1, 2 or 3 before stacking. This approach worked well and this heap has been successfully operated for 15 years. Understandably, any such approach requires upfront mapping of the geotechnical properties of each major ore type in the same manner as the properties relevant to production. Considering that the mining sequence will deliver different ore types in different relative proportions over time, targeting a specific blend will not always be practical. Nevertheless, characterizing the geotechnical and metallurgical properties of each ore type will allow the definition of the operating window, the customization of predictive modeling tools, and the adequate formulation of operational controls.

Ore as the overliner gravel

The purpose of the overliner is to protect the liner from puncture and other mechanical damage, provide a free-draining layer at the base of the heap, and protect the leachate collection pipes from the loads induced by construction traffic, the stacking equipment and the heap itself. With frequent lack of availability of gravel onsite, and increasing cost in producing or procuring it from offsite, crushed ore is a natural candidate. However, there are two main constraints: long-term permeability of the leached ore (commonly called "ripios" in South America) and ore production scheduling, especially for the pre-production or first phase of construction.

Geotechnical testing of ore ranges from a cursory analysis of fresh ore, to a rigorous consideration of how the properties may change with aging or exposure to leach solutions. Some ores are very durable and undergo negligible degradation even under prolonged leaching. The geotechnical evaluation of these ores is relatively simple once the overall durability has been established (there are various ways to do this, a discussion of which is beyond the scope of this paper). However, for most ores leached in an acidic environment, the potential for long-term degradation of the ripios is an important concern, and the long-term permeability must be established before it can be considered as overliner gravel.

Ripios or leached ore can be used for overliner generally in two ways: as a partial layer acting in conjunction with a higher quality material such as gravel or a geosynthetic; or for the entire overliner blanket. The latter is generally the goal, but is not always achievable as some ripios will continue to degrade with continuing exposure to leach solutions. Figure 1 presents an example of unacceptable long-term degradation, where the permeability after multiple leach cycles falls below that required for adequate heap drainage.

The combined approach can be implemented in two ways: vertical or horizontal layering. Vertical layering is relatively common for dynamic heaps where the overliner layer tends to be very thick (often over 1 m); the bottom layer may be high quality gravel and the upper layer can be less reliable material such as leached ore, which may degrade, but within predictable and acceptable limits. Horizontal layering can be achieved by alternate strips of manufactured gravel and ripios. This approach was used at a copper mine in Chile to reduce the gravel cost. In that case, the leachate collection system was designed to maintain the hydraulic head over the liner at less than 1 m with negligible drainage contribution credited to the ripios strips. In other words, engineered gravel was used for drainage and the ripios only provided geomembrane protection.

Scheduling of ore production can be a critical issue for the first phase of the leach pad when the entire plant is being constructed and commissioned simultaneously. In such cases the assumption of ore availability should be tested against the mine plan and the construction schedule. For subsequent phases, the availability tends to be less of an issue and comes down to selecting (and possibly stockpiling) the best quality material.

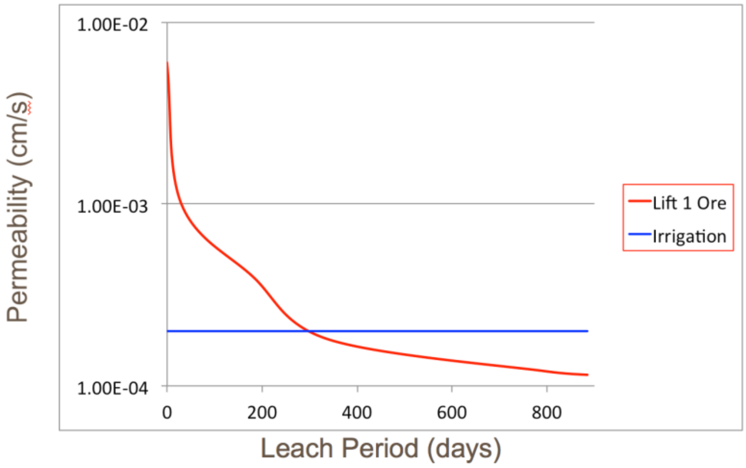

Figure 1: Ripios permeability as a function of leach time (copper ore, Chile)

Overliner placement on slopes

Overliner placement on the leach pad during the first phase of construction is generally a part of the civil construction package. For subsequent pad expansions this responsibility often falls to operations. Other than the quality of the gravel, the key issues tend to be overliner thickness control (to ensure safe separation between heavy equipment and the liner) and the stresses induced on the liner due to overliner weight and mobile equipment. The importance of these is amplified for pads with steep and especially variable slopes. Steep slopes increase the transfer of stress to the geomembrane, creating a risk of puncturing and tearing of the liner or seams. Variable slopes, as encountered in terrain-contouring pads and the transition from the valley bottom to side slopes in valley leach pads, are especially problematic because it can be difficult to know the thickness of the gravel near the working face. In spite of these complexities, in several facilities in South America overliner placement is required everywhere including the relatively steep slopes of terrain-contouring or valley leach pads. One argument given by the proponents is that, in addition to protection against liner puncture, the overliner protects against direct ultraviolet exposure and other kinds of accidental wear and tear, which can occur before the area is covered with ore. However, it is the authors' experience that most serious damage to geomembranes occurs during placement of the cover layer; thus, to the extent that the cover can be either eliminated or replaced with geosynthetics, it is wise to do so.

Temperature effects

Some of the acid and biological leaching processes involve exothermic reactions or require the pre-heating of irrigation solutions, while most leach pad liners and drainage pipes are thermoplastic. Thus, an analysis of the temperature rise inside the heap and its impact on liner puncture resistance and loss of structural integrity of the pipe can be crucial (Sinha and Smith, 2012; Smith, 2011). This fact, although often overlooked, should be integrated into design.

First lift stability

The importance of stability of the heap is well understood, and slope stability analyses are routinely performed by geotechnical engineers. Common sense suggests, and rightly so, that all other factors remaining the same, the higher the pile the lower the safety factor against slope failure; thus, designs are generally based on the stability of the ultimate height of the pile. In reality, all other factors do not remain the same, however. The stacked ore is not compacted in order to provide for free drainage of the leachate. In multi-lift operations, as additional lifts are stacked the first lift does get compacted due to both self-weight and mobile equipment. Thus, its shear strength tends to increase. Furthermore, due to benches provided between lifts, the overall slope of the heap decreases as additional lifts are placed. These two factors – the lowest shear strength and the steepest effective slope – combined with the close proximity of the relatively weak liner interface often result in a lower factor of safety against slope failure for the first one or two lifts of a heap. This risk is not hypothetical; according to Breitenbach (2013), approximately 60% of heap slope failures occur in the first few lifts.

Commissioning

Agglomerate production

A significant number of heap leaching projects suffer because of the inability to produce quality agglomerates, which in turn affects geotechnical behavior and leach kinetics (Caceres, 2013). This tends to be worse at start-up because:

1. Operators lack experience with the particular ore (and sometimes more generally).
2. Ore produced at the start-up tends to be more weathered and thus most sensitive to agglomeration methods.
3. Early production ore tends to be stacked in the more critical parts of the heap (which affects life-of-mine (LOM) behavior), and this is even more important for valley leach pads.

A key reason for the lack of consistent production of quality agglomerates is a lack of understanding of the variability in the ore types mined at different times and from different locations. Properties such as particle size distribution, clay content, moisture content, hardness or durability, and so forth govern the agglomerate quality. If the variation in these properties is significant the common use of average or typical ore characteristics will not work well. In which case a more sensible approach would be to develop a geotechnical model of the ore body similar to, but less detailed than, the metallurgical model. Agglomeration properties and the resulting ore behavior can then be predicted based on the mine plan. The level of rigor required will depend on the degree of variation and the nature of the least desirable ore.

Stacking direction

The importance of stacking direction on slope stability has become well recognized during the last decade. In order to allow the leachate flow without restrictions and ponding, leach pads are designed to have downward slopes, generally in the range of 1% to 5%. As demonstrated by Smith and Giroud (2000), on a planer pad with a downslope gradient, the potential for failure of the advancing face of the heap is greater for down-gradient stacking than for up-gradient. The lower shear strength of the liner interface generally forces a failure surface through the stacked ore to continue along the top or bottom interface (Figure 2 a), and the tangential component (along the liner interface) of the weight of the failing block helps the down-gradient movement. The tangential component of the weight of the stacking equipment (for a truck dump operation) supplements that of the weight of the ore and further improves or degrades the stability for up- or down-gradient stacking, respectively.

For practical reasons, most heap leach pads are not designed to tight elevation control and local variations within the specified range of slope are ever present. Smith and Giroud (2000) used the same reasoning as given above to show that local variation causing a steeper gradient at the front end of the pile induce lower factors of safety against slope failure in case of stacking in the down-gradient direction as compared to up-gradient stacking (Figure 2 b).

An additional factor against down-gradient stacking is a greater likelihood of the strain required to mobilize peak strength being exceeded and thus mobilization of post-peak interface strength. Since the interface along the bottom of the geomembrane is generally weaker than the top interface, there is a greater tendency for the liner system to move along with the ore. This is amply demonstrated during the overliner placement. There is a sharp increase in the size and frequency of geomembrane wrinkles in front of the advancing face when the direction of spreading is in the down-gradient direction; this in itself is good enough reason against both down-gradient stacking and overliner placement.

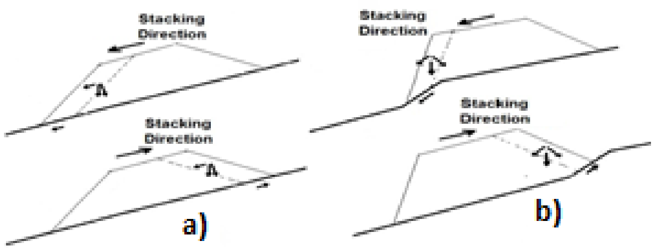

Figure 2: Up-gradient and down-gradient stacking on a) uniform slope and b) locally varying slope

First wetting of fresh ore

Assuming the heap to be saturated and a laminar flow of solution through it, the permeability and the irrigation rate can be related through Darcy's Law. For example, for an irrigation rate of 7.5 L/h/m^2 the required minimum saturated permeability would be 2E-4 cm/s. For practical reasons including a lack of complete understanding of the ore, a higher permeability would be required and designers commonly use two to ten times that figure. However, this figure refers to the saturated permeability while heaps do not, and should not, generally operate at full saturation. When fresh ore is stacked, the degree of saturation will be well below 50% even for agglomerated ores, and the unsaturated permeability can be much less than the saturated permeability. Thus, even for an ore with an acceptable but modest saturated permeability, the heap may not be able to tolerate full-rate irrigation until the degree of saturation increases sufficiently. In such cases the initial irrigation should be either at a reduced flow rate or for reduced hours per day (also called "pulse" irrigation). Failure to do so can result in surface ponding and runoff, erosion, localized slope failures, and solution channeling within the heap (Caceres, 2013).

Operations

Unorthodox operational procedures

At times during operation, some non-standard procedures are adopted with perfectly good intent and focused on resolving an obvious issue, but without considering the ancillary negative impacts, which may or may not be so obvious. One example of this situation with an extreme and unfortunate consequence is an incident at a copper mine in Chile. A 7.5 m high dynamic heap was being stacked using a stacker with an overhead tripper car. The ore was stacked at its natural angle of repose. Safety considerations for workers walking up and down the slope in order to install and check the sprinkler system resulted in flattening of the slopes with excavators. This perfectly well-meaning safety act created an exposed and unsupported vertical face at the transition between the freshly stacked ore (at its angle of repose) and the previously flattened slopes, resulting in a slope failure, several injuries and one fatality. The usual procedure to facilitate the traffic up and down the slope is to simply provide portable stairs, steps or ladders.

Static liquefaction

Although liquefaction flow slides under conventional static loading conditions have occurred in the mining world and are well documented (e.g. Davies et al., 2002), these have been invariably in reference to tailings impoundments and coal (fly ash) waste dumps. In recent years, heap stacking with thicker lifts, lower permeability and weaker ores, and in some cases flooding the heaps, the possibility of heap failure due to static liquefaction has rightfully drawn some attention. Thiel and Smith (2004) have given a list of some indicators and their threshold values for liquefaction in leach heaps. Recently at a Peruvian mine, a slope failure was induced by the rising phreatic level in the heap, possibly aggravated by a small excavation at the toe of the heap. Whether liquefaction actually transpired in this case is difficult to establish, but this example is a reminder that static liquefaction for leach heaps could be a reality as already established for tailings impoundments.

Over irrigation

The optimum irrigation rate is generally determined based on a combination of geotechnical (principally permeability) and metallurgical (leach kinetics and reagent consumption) properties. Excessive irrigation, however, often results from a variety of factors including: unexpected decrease in permeability with increasing pile height and aging, initial wetting, additional flows due to heavy precipitation (for tropical regions), and a host of other factors. Sometimes heaps are irrigated at excessive irrigation rates intentionally, to either increase metal production or make up for down time. Intuitively, it seems natural to think that a higher irrigation rate will improve leach kinetics, but there are geotechnical risks involved. At a Peruvian mine, the irrigation rate being used is almost double that of the design rate, the geotechnical risks overlooked or at least outweighed by the intended production gain. In reality, increasing the rate of irrigation beyond the natural limit imposed by minimum permeability (which in turn is a function of ore grain-size distribution, agglomeration, stacking procedure, particle segregation) can do more harm than good by way of flooding, ponding, short-circuiting and channeling through coarser material and reduced direct solution contact of finer particles. Many heaps are designed for saturation around or a little over 50% during leaching. If the applied irrigation rate increases saturation to 80% or 85%, the heap starts to behave as a saturated mass with the inherent slope instability and liquefaction susceptibility. Additionally, over-irrigation can dilute the PLS, increase lixiviant requirements and make metal extraction less efficient.

Increasing heap size and production rate

It is nearly universal to consider expansion or other modifications of an operating heap to increase production. Geotechnical analyses at the design stage produce a specific heap design in accordance with the established design criteria, typically expressed in terms of details such as heap height, lift thickness, bench width, rate-of-rise of the heap, liner system, etc. Most of these are coupled to some degree and a subsequent change in one may require changing others. For example, a change in the heap height is likely to affect slope stability and will require a revised stability analysis and possibly changes in the overall slope. Higher stresses on the liner may require a more robust liner system. A change in the rate-of-rise of the heap, often driven by the intent of higher production rates, may require a change in irrigation rate and leach cycle, and the overall effect could be an increase in the potential for static liquefaction. Increasing the area under irrigation will require re-evaluation of the drainage system capacity and the surplus water storage capacity (i.e., the events pond).

Unfortunately, in general the geotechnical engineers do not state these intertwined relationships clearly enough and some changes are made during operation without due consideration of the coupled effects. It is true that some of these operational changes are foreseeable and a matter of common experience. But more generally, robust change management is the optimal way to avoid such conflicts.

Underestimation of the significance of geotechnical issues

At times, the lack of a complete understanding of cause and effect, and their interlinking across the traditional discipline boundaries, becomes problematic in identifying and resolving an issue. For example, geotechnical problems often affect metal production as directly as a metallurgical problem. Ignoring this multifaceted nature of the problem often results in partial solutions only, as demonstrated by the example below.

In a copper bio-leach facility in South America the operators identified a problem with higher than expected moisture content in the heap, sufficiently serious that heap stability might have been at risk. This triggered a call for further geotechnical investigations and the formulation of a slope stabilization program. However, high degrees of saturation also suggested a lack of airflow, which suppressed kinetics. Slow kinetics reduced internal heat generation and resulted in a lower-than-predicted operating temperature, which caused further suppression of the biological leaching. In other words, the geotechnical issues were a symptom of a leaching problem. Rather than slope buttressing, the cause of the poor drainage and suppressed kinetics became the focus of the investigation.

Dynamic heap overliner damage

Repeated stacking and removal of ore lifts for a dynamic heap requires heavy equipment (stackers, conveyors, dump trucks and loaders) moving directly on the overliner layer, which can cause crushing. This results in a loss of drainage and possibly traffic support capacity. Thus, in time, the overliner material neither provides a permeable layer for the leachate collection, nor does it adequately protect the drainage pipes or the liner. In essence, the very purpose of providing overliner is defeated. The operational team has to be made aware of these issues and provided guidelines for monitoring performance and thresholds for when and how a geotechnical engineer should be engaged.

Poor irrigation

Lack of routine inspection and proper maintenance of the irrigation system often allows broken lines and clogged emitters to go undetected. Understandably, this results in uneven distribution of solution across the surface, with some spots remaining dry and others receiving excessive flow that causes ponding and flooding. The situation is aggravated in the case of a multi-lift operation, resulting in fully saturated pockets trapped inside the pile providing zones conducive to liquefaction. In other cases, the irrigation can reduce the permeability of the surface of the ore, either by directly degrading agglomerates (especially when sprinklers are used) or causing fines migration. Figure 3 shows a rather unique situation for carbonate leaching of uranium ore: ponding due to plugging by algae formation in the warm, modest pH solutions.

Figure 3: Uranium heap with algae-induced surface plugging (Namibia)

In recent years, a number of automated tools have been developed for monitoring and detecting operational failures in the irrigation system. These have not yet received widespread acceptance, but the technology is very promising. Some systems have been developed specifically for detecting saturated and dry areas in heaps, and may also be capable of detecting pipe leaks, pipe breaks, plugged sprinklers and other failures in the dripping system very rapidly.

Particle segregation

Particle segregation occurs at every step of ore handling, from mucking benches to stockpiling to stacking on the heap. The key is to identify when segregation is excessive; that is, when it will create performance problems in the heap. Segregation tends to concentrate larger rocks at the base of a pile and finer material near the top. Uncontrolled segregation can give rise to a host of both geotechnical and process issues: preferential flow paths or solution channeling, incomplete metal recovery, suppressed kinetics, static liquefaction, and slope instability being some of these (Smith and Thiel, 2004).

Closure

Closure planning is generally focused on early project approvals, including environmental reviews and permitting. Many operations thereafter perform periodic updates, but it is rare that these are done in detail. In other words, closure "designs" are generally held at the conceptual level until the last years or even months of operations. Thus, closure issues do not provide operational feedback as many other issues do. Some of the often-encountered closure issues listed here could certainly be alleviated through proper characterization and integration, and treating closure as a continuum of design and operations rather than a set of discrete acts at the end of the project's life.

Inadequate scheduling

Any significant change from the original design calls for an assessment of the impacts on all other project phases. The impact of a design change on closure is often seen as remote in time and this causes it to receive less attention than would otherwise be the case. For example, if the heap height is increased from the original design, updated slope stability analyses, construction rescheduling, and possibly some additional stabilizing measures and adjustment in the irrigation systems may be necessary and these needs will usually be self-evident. If the same sense of connectivity is not applied to closure, the longer-term impacts on closure issues such as rinse time and slope regarding requirements may go unrecognized.

Water balance

During operations, the water demand is driven principally by two factors: evaporation and the water required to increase the moisture content of the ore from as-mined to the in-leach condition. For sites with strong net water demands the change from operations to closure brings a reduction in demand in the form of water required to wet the fresh ore. This is generally easily accommodated. However, for sites with near-neutral or surplus operational water balance there can be significant increases in the quantity of surplus water as the rate of new ore feed to the heap is reduced and eventually halted. For example, for a heap receiving 30,000 tpd of fresh ore, which requires 10% additional moisture during leaching, the cessation of stacking can increase surplus water by 3,000 m^3/d in the short term. This water may require storage, treatment for discharge, or forced evaporation.

Closure geometry

It goes without saying that stacking the heap consistent with the intended closure geometry will avoid regrading and could have a significant cost impact. For the same reason (a sense of time remoteness from the closure phase), this is not always followed through during operations. If the closure criteria requires that the heap slopes be 2.5 horizontal to 1 vertical, then stacking the heap at 2h:1v may save a little money during operations by reducing the leach pad area required, but disproportionately increase the closure liability. Equally or more important is surface water control. To the extent that the toes and crest of the heap can be stacked consistent with long-term surface water diversion, implementing and maintaining closure will be easier.

Waste disposal

Various types of wastes are produced in many operations. Integrating these wastes to produce synergies at and after closure may have definite advantages in terms of optimizing the disposal processes, space and management. Such synergies could, for example, be achieved by comingling drainage from an alkaline heap with an acidic waste dump. It must be pointed out, however, that comingling acidic and alkaline wastes could initiate some chemical reactions with undesirable and even dangerous characteristics. In one study for a nickel heap leach facility, the authors found that mixing of high and low pH plant residues produced carbon dioxide gas in laboratory samples (Smith and Christie, 2015). Under full-scale conditions, this could pose worker safety issues at the active dump face as well as induce excess pore pressures in the dump, aggravating liquefaction risks. Additionally, predicting the geochemically-driven long-term changes to geotechnical properties in such comingled wastes becomes important for stability and safety considerations. This in itself is a difficult task and would require both geochemical and geotechnical testing of samples aged under simulated waste pile condition. Long-term predictions based on short- or intermediate-term laboratory tests could even necessitate complex geochemical modeling and extrapolation. All these suggest the need for a thorough investigation before opting to comingle wastes.

Valley leach pads (VLPs)

Closure issues for VLPs, especially those with internal ponds, present a special concern with respect to the stability berm. In the absence of adequate preventive measures, the stability berm might impound water in the heap long after closure, requiring management as an active water-retaining dam. This becomes a long-term risk as well as an economic, environmental and regulatory issue (Breitenbach and Smith, 2012). Another key issue is the ore depth, which is both greater and more variable than for conventional leach pads. This affects the time to rinse the heap to the target water quality and limits the ability to perform concurrent closure. Heaps are rinsed to recover as much as possible of the metal of interest trapped in the held solution as well as for environmental reasons. Effective rinsing of VLPs is more challenging as compared to heaps on flat pads, but there are regulatory criteria for rinsing and the practice is almost universal.

Closure costs

Since 1995 mine closure costs have been increasing at an average annual rate of 3.9% net of inflation (Wilson, et al., 2007). Much of this escalation is due to earthworks costs. Pencock (2000) reports that underestimating earthworks and the failure to adequately consider location-specific issues are often the primary cause of overruns. Typical cost overruns for capital projects have been 20% to 60% since 1965, and this has not self-corrected in the 50 years of available data (Haubrich, 2014) – and there is some suggestion this is getting worse. Consider that the average actual closure cost for an Australian mine is 6.8 times the estimated cost, and in the USA the total mine closure liability is $12 billion more than the bonded amount (Caldwell, 2007). Some of the geotechnical issues driving cost escalation include: incomplete site-characterization from closure and post-closure perspectives, inadequate quantity or quality of borrow materials, operational decisions that increase closure liability such as stacking heaps overly steep, and failure to maximize concurrent closure.

Summary

Depleting high-grade ores and increasing demand for certain metals have made heap leaching an attractive processing technology and there is a drive for bigger and higher heaps – heaps as high as 200 m are being considered. With this comes greater challenges for the geotechnical and the operational teams alike, requiring: i) greater collaboration between the geotechnical and the process engineers throughout the project; and ii) all sides having a better understanding of both operational and geotechnical details and their interlinking. While the overall design procedures, construction methodology and operation techniques have kept pace with the increasing complexities, intermediate details and the connectivity of geotechnical and operational factors are often ignored or not realized. Some of the often-forgotten considerations that must be paid heed are the importance of accounting for variability in the geotechnical and metallurgical properties of ore throughout a well-planned integrated test work program, the subtleties of heap stability, overliner placement on steep slopes, the implications of high irrigation rates, the impact of design changes on closure, and the need for contingency measures to deal with water management during closure.

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