Design considerations for impounding valley leach pads vs. conventional

by Allan Breitenbach and Mark Smith

Oversteepened slopes at Barrick's Pierina gold mine in Peru.

Leaching has been used since the 1600s on unlined ore dumps and since the late 1970s on lined leach pads for the recovery of metals from mined ore, the latter typically called "heap" leaching and the former "dump" leaching. Modern day run-of-mine (ROM) or crushed ore heaps are stacked in controlled lifts on lined leach pads and irrigated with a solvent solution (dilute alkaline cyanide for precious meals, dilute sulfuric acid for base metals and uranium). Conventional lined leach pads store process solutions and any storm water, snow melt and cumulative wet season surplus water by gravity flow to external ponds. Impounding valley leach pads (also known as valley fill heaps) differ from conventional leach pads by storing various combinations of process liquid solution and surplus water within internal ponds by using the interstitial pore volume of the ore.

While impounding liquids within the heap is simple in concept, impounding leach pads are more complicated for construction and containment compared to conventional leach pads with external ponds.

The identifying trait that distinguishes valley leach pads (VLP) from conventional leach pads (CLP) is that two or three sides of the heap are contained by natural valley wall topography. This also tends to result in a relatively steep longitudinal slope (the axis of the valley), often in excess of 10-to-15 percent, compared to CLP slopes controlled by site grading fill at typically 1-to-5 percent downhill grades. For this reason, VLPs commonly require a buttress berm fill at the downstream toe to improve heap stability. This buttress can then be used to create an internal impoundment. This article considers the advantages and disadvantages of using internal VLP impoundments as compared to external impoundments for CLPs and non-impounding VLPs.

Historic background

The first large-scale heap leach projects were copper dump leach facilities. They used only natural containment (occasionally enhanced with local use of compacted soil or clay liners (CCL), cut-off or interceptor trenches). With gold and, to a lesser degree, silver heap leaching, cyanide was introduced starting in the western United States in the mid-1970s and natural containment was no longer viable for environmental reasons.

Beginning in about 1974 in Nevada, most of the first gold and silver operations used low permeability compacted soil liners such as CCL. By 1983, geomembrane liners were becoming more common and

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Building the leach pad in 2007 at Minefinders' Dolores gold mine in Sonora, Mexico.

quickly became the standard for cyanide operations, with the last clay-only gold heap leach pad in the U.S. being constructed in the mid-1990s.

Large-scale copper heap leaching began in Chile in 1980 with the Los Aquirre project. By the early 1990s, Chile had about 10 major copper heap leach projects, most using lined conventional leach pad technology (Breitenbach and Smith, 2006). Copper heap leaching in the U.S. started with unlined ROM leach dumps. Only three lined copper heap leach pads were constructed in the 1980s. Chile is now home to several of the world's largest leach pads, measured both in containment area (several million square meters) and contained ore tonnage (in excess of 1 Gt or 1.1 billion st). The average leach pad area is now about 1 Mm^2 (10.7 million sq ft) and projects are in the planning stages for leach pads in excess of 10 Mm^2 (107 million sq ft) in Turkey, Burma and Africa. Essentially, all of these are geomembrane lined.

Valley leach pad technology was first introduced at the Zortman-Landusky gold mine in Montana in 1979. That operation was followed by Mercur gold (Utah), Summitville gold (Colorado), Rochester silver (Nevada) and Basin Creek gold (Montana), all between 1985 and 1987. Two of those early projects, Zortman-Landusky and Summitville, experienced significant performance problems, ultimately becoming listed as Superfund sites due principally to containment problems.

The Carlota heap project in Arizona, commissioned in 2009, was the first lined copper ore VLP in the U.S. By 2012, that project was being decommissioned due to ore leaching and especially ore permeability problems.

Fast forward to the present and leaching is a major contributor to global gold, silver and copper production and significant efforts under way to commercialize it for nickel and uranium (Smith and Amini, 2010; Smith and Steemson, 2009). The authors are not aware of any authoritive estimates of heap leach metal production as a fraction of the total. Some informal estimates put the total number of gold and copper mines using heap leaching for at least part of their production as high as 75 percent and the metal production at more than 25 percent of the worldwide total. There are now some 17 impounding valley leach pads (including six in planning and not yet constructed) and another 22 nonimpounding VLPs either constructed or planned. Table 1 lists the impounding VLPs known by the authors.

Considerations for internal pond systems

General. The general list of key VLP performance categories for comparison to fully-drained heaps (CLPs and non-impounding VLPs) include the following:

- Earthworks and land disturbance.
- Pond and solution management.
- Leaching and kinetics.
- Slope stability.
- Containment system.
- Construction and commissioning.
- Surface water management.
- Closure.

Earthworks and land disturbance

Valley leach pads are generally dictated by the terrain rather than selected for their advantages. They are suitable to terrain that would otherwise require vast amounts of earthworks to create a more suitable "level" platform for stacking the ore. The main advantage is a drastic reduction in earthworks and the related land disturbance. Once VLP technology has been elected, there is the option to create an internal impoundment or a smaller internal pond for day-to-day operational storage and pumping with external ponds for gravity draindown and storm overflows or down time for any pump maintenance.

On the other hand, steep slopes and tight valley terrain make everything about the leach pad more complicated, from sequencing construction and ore stacking, to managing surface waters and creating access roads. Construction in a natural valley will also encounter more troublesome geotechnical issues, including abundant springs and creeks (common in any site with more than about 300 mm or 11.8 in. annual average rainfall), peat and organic clay deposits and, thin and variable soil cover.

Table 1

Known impounding lined valley leach pads.

Project, owner and year commissioned	Location (USA unless noted)	Metal	Ore depth (m)	Operation status	Comments
Zortman-Landusky, Pegasas, 1979	Montana	Au	<60	Closed	Multiple VLPs, ultimately became EPA Superfund site.
Mercur, Barrick, 1986	Utah	Au	<50	Closed	
Summitville, Galactic, 1986	Colorado	Au	50	Closed	Ultimately became EPA Superfund site.
Rochester, Pegasus, 1986	Nevada	Ag/Au	50	Operational	
Basin Creek, Pegasus, 1987	Montana	Au	?	Closed	Partial gravity pipeline drainage through liner.
Cripple Creek, Anglo Gold, 1995	Colorado	Au	125	Operational	
Pierina, Barrick, 1998	Peru	Au	145	Operational	95 m (toe-to-crest) rock fill dam.
Veladero, Barrick, 2006	Argentina	Au	130	Operational	Original commissioned as impounding; due to high leakage rates changed design to minimize impoundment use.
Carlota, Quadra FNX, 2009	Arizona	Cu	125	In closure 2012	20-m high dam, ore percolation problems caused early decommissioning.
Dolores, Minefinders, 2009	Sonora, Mexico	Au	100	Operational	Originally commissioned to impound pregnant solution only; expansion design eliminated impoundment.
Los Filos, Agnico, (year unknown)	Sonora, Mexico	Au	<50	Operational	
Camaraks, 2012	Canada	Cu	?	Construction unknown	
Fort Knox, Kinross, 2012	Alaska	Au	152	Operation	
Werter, Finders Resources, 2013	Indonesia	Cu		Construction	
Eagle Project, Victoria Gold Corp, 2014	Canada	Au	250	Construction 2013	55-m high dam.
Gas Hills, 2015	Wyoming	U	60	Feasibility	15-m startup berm.
Confidential project, 2015	Peru	Cu	>160	Feasibility	Whether or not this will be impounding is under study.

Pipe penetrating the buttress at Minefinders' Dolores gold mine in Sonora, Mexico, circa 2007.

Pond and solution management

Internal solution storage relies on the field capacity of the ore (the difference between moisture content under free drainage and saturated), generally less than 20 percent of the total volume in the impoundment. Thus, for any given storage volume, an impoundment of approximately five times that volume must be created. This impoundment requires both a robust liner system (generally double geomembranes with clay or GCL under the bottom geomembrane) and a dam to create the impoundment. This can be expensive and, thus, the goal tends to be to minimize the required internal storage capacity. The larger pond volume also tends to produce much deeper water depths than external ponds. As an example, at Barrick's Pierina gold mine in Peru, the maximum depth of solution in the internal pond is 45 m (147 ft), three-times a typical large external pond. This results in more stress on the liner (and thus more risk of defects) and increased leakage rates for the same defect size and frequency. This requires an upgraded top liner and a higher capacity leak collection or LCRS layer. Note that leakage through a uniform defect in geomembranes underlain by a permeable LCRS is governed by the following equation that shows that leakage rate increases as the square root of hydraulic head:

$$Q = 0.6 \text{ x } a \text{ x } (2 \text{ x } g \text{ x } h)^{0.5} \qquad (1)$$

where Q = leakage rate, a = area of hole, g = acceleration due to gravity and h = hydrostatic head.

There are several factors that affect field capacity of leached ore and, thus, the in-heap pond ore storage capacity, including:

- Multi-lift primary load settlement of the lower ore lifts.
- Long-term secondary or creep settlement from both rearranging of the rock-to-rock particle contacts and any chemical degradation and weakening of the rock particle strength over the operating life.
- Allowance for storage reduction from the migration of any leached ore fines into the pond area.
- Lost storage from the pumping drawdown curve to maintain the maximum and minimum solution pond sump levels required for seasonal pump operations.

The internal pond volume storage capacity varies depending on site-specific available heap drain fill materials, interconnecting drain pipe designs and pump operations that impact the overall VLP pond performance.

There are two options to take the solution out of the internal pond — gravity drains through the liner system and dam, or pumps in vertical caissons. Both are higher risk than most drainage facilities. Penetrating pipes routinely fail. For this reason, the authors will not use them for VLPs, since such a failure is both irreparable for all but the smallest buttresses and puts the buttress stability in grave danger. Vertical pump caissons or "cans" are subject to extreme and differential forces and buckling. Loss of vertical alignment or collapse are all common scenarios for which case many engineers design for 200 percent or more surplus capacity (that is, one spare caisson for each one in service).

Leaching and kinetics

To take advantage of the internal impoundment, the bottom of the heap must, by definition, be saturated at least seasonally. This exposes the already-leached ore to pregnant solution for the entire life of the operation. This can increase metal recovery but can also increase reagent consumption and cause greater degradation of the leached ore, which, in turn, reduces its strength, permeability and field capacity. Ore submerged by the internal pond lacks oxygen, and leaching can become minimal below the pond solution level.

Any VLP, impounding or otherwise, will have a much deeper maximum ore depth than a CLP for the same ore capacity and area. For a VLP, the ore depth will vary greatly, from near zero along the perimeter to the maximum over the valley axis. All heaps suffer from differential leaching due to depth variability, but this is greatly exaggerated in VLPs.

Slope stability

Geotechnical engineers typically consider slope stability under both normal and earthquake loading conditions. The former is routinely called static stability. Earthquake loading is generally modeled using either the pseudo-static method (where the earthquake loads are treated as additional static loads) or dynamic methods (where the cyclic nature of the seismic loads are simulated). Earthquakes can cause slope failures by adding loads to the heap due to the ground acceleration and by inducing what is known as liquefaction (addressed later in this article).

An impounding VLP stores solution in-heap at the critical downhill toe limits with a multiple-layer liner system, and each layer presents a weak interface. The strength reduction is caused by planar synthetic-to-synthetic liner and synthetic-to-clay interface surfaces that impact initial valley fill placement and subsequent high lift loads. Most leach pad liner failures have occurred during initial dynamic downhill truck traffic loads into the valley bottom or during initial ore lift placement (Breitenbach, 1997). Thus, the likelihood of failure for an impounding heap can be significantly higher than for a drained heap. Further, the failure of a saturated mass poses much higher potential consequences of a failure since that mass can fluidize during failure, and increase the involved volume and run-out distances.

Valley leach operations generally include a range of ROM to coarse to fine crushed ore with rock strength versus confining stress loads, at least for the coarser ores, generally estimated from literature (Leps 1970 for rock fills and NAVFAC 1982 for crushed granular ore). Acid leaching for copper and uranium valley heap leach operations can alter and weaken the rock particles compared to cyanide alkaline leaching for gold and silver operations. Therefore, the potential for poor drainage and weaker rock material strength and consolidation should be a consideration in slope stability, which is most critical for an impounding heap. And such degradation can increase the degree of saturation over time.

Fully drained heaps are significantly less susceptible to earthquake instability at the critical downhill toe limits, where heap solution control is critical to continuous ore production, heap stacking and leaching operations. There are no known drained heap slope failures induced by earthquakes, and such heaps have been subject to up to 8.4 magnitude earthquake events at a measured PGA of 0.22 g (Breitenbach and Thiel, 2005). On the other hand, there are at least two known earthquake-induced failures of saturated heap slopes: Cerro Verde and Cuajone, both in southern Peru. Both of these were unintentionally impounding due to very low ore permeability relative to the irrigation rates, and the slope failures were caused by liquefaction (discussed later in this section).

Therefore, a saturated slope requires a higher safety factor against static and earthquake-induced slope failures. Water storage dams typically require a minimum static safety factor of 1.5 and pseudo-static (earthquake) safety factor of 1.2 (ICOLD 1995 standards). A fully drained, low-risk heap requires a lower minimum safety standard, commonly 1.3 static and 1.0 pseudo-static. The design features to achieve the higher safety factor can be complicated and expensive. The pseudo-static method applies to mine sites located in low to moderate seismicity regions where the peak ground acceleration (PGA) is 0.15 g or less, based on the performance of earth- and rock-fill dams subjected to a range of about 5 to 8 magnitude earthquakes (Seed, 1979). A dynamic stability analysis generally is not required for fully drained heap leach pads, since a fully drained heap does not pond water, is not normally susceptible to liquefaction and is, thus, not a high hazard structure. But most impounding heaps should be subjected to fully dynamic analysis if there is any significant seismic risk.

Liquefaction occurs when pore pressures increase to equal the material's shear strength, allowing the material to flow like a viscous liquid. Pore pressures can increase during an earthquake because the individual grains or

Site preparation in a valley at the Dolores gold mine in Sonora, Mexico in 2007.

The Mulatos gold mine in Mexico. circa 2010.

particles are closing saturated pore space faster than the pore water can escape. To be susceptible to liquefaction, a material needs to be nearly saturated (>85 percent is a common rule of thumb), of sufficiently low permeability to restrict drainage when a load is applied, and be subjected to a rapidly applied load, most commonly an earthquake. Liquefaction failures are also known as flow slide failures and are known to travel several kilometers and have caused some of the highest fatality events in mining. Liquefaction of the underlying slimes layer was the cause of the now-infamous Kingston Fossil Plant tailings failure, the remediation bill for which exceeded US$1 billion in 2011. A properly behaving, well drained CLP has very low susceptibility to liquefaction failures, while an impounding VLP with moderate to low permeability ore at full pond conditions can be very susceptible.

Containment system

The internal pond liner system generally requires a more robust and more flexible liner to handle the aggressive loading and high hydraulic head. This includes loads due to extreme ore depths, the resulting differential foundation settlement (including settlement along the inside face of the dam), much higher hydraulic heads, high puncture loads, high soil arching loads transferred to the liner adjacent to the larger diameter drain pipes, differential multi-axial liner deformation, vertical down-drag loading on the slope liners and pump caissons from initial dry loose lift placement to wetted and loaded ore, and lower strength geosynthetic interfaces.

Liner puncture resistance testing should also consider longer time intervals and the approximately 30 percent increase in the ultimate load to better simulate the soil arching load transfer from the major and secondary pad drain pipe areas to the adjacent liner surfaces (Breitenbach & Khoury 2010; Leduc & Smith, 2004). While both also apply to CLPs, since the drainage pipes all converge in the same location and those are near the outlet works and where the hydraulic head is the greatest, it is much more critical that these are adequately addressed in a VLP.

The pump caissons will have potentially very large down-drag forces along the walls, and this needs to be addressed in both design and construction. A combination of friction breaks (e.g., wrapping the outside of the caissons with geomembrane), allowing the caissons to telescope, and providing a proper foundation have been successful in managing these loads. However, experience has shown that these are prone to problems: the concentrated loads at the base can be extreme, which can produce differential settlement and liner rupture; and buckling or misalignment of the vertical axis of the caissons are common.

Top or primary liner leakage in the impoundment, beyond acceptable limits, can be considered an operational fatal flaw, since repair of the buried pond liner would require cessation of stacking and leaching operations and removal of the already-stacked ore. Unless such leakage was to manifest very early in the life of the heap, the defects would be, for all practical purposes, impossible to repair. This is an increasingly important issue, as governments and communities are increasingly intolerant of leakage and the perceived environmental risks. This has been a reoccurring problem in several gold VLPs in the past, including the Summitville in Colorado, the Zortman-Landusky in Montana, and, more recently, Veladero in the Argentine Andes.

Construction and commissioning

Grading steep slopes, and especially constructing complex detail work such as diversion channels, liner anchor trenches and clay liners, experience sharply escalated unit costs and unexpected construction delays. And working on steep terrain is inherently more dangerous for the construction workers.

One constraint commonly overlooked by the designer is the need to create a sufficiently large irrigation area in the first lifts of ore, where the narrow bottom of the valley tends to

Rain coats at the Pierina gold mine in Peru, circa 2003.

make for very small lift areas. This is especially problematic in ores with long leach cycles, such as copper. For such ores, the standard approach is to fill the valley bottom with structural fill beneath the liner to create the needed area. In the extreme, the entire valley is filled, creating a conventional pad in a valley setting, such as has been done at Freeport-McMoRan's Cerro Verde copper mine near Arequipa, Peru. For ores with faster kinetics, the common approach is to simply increase the thickness of the first few lifts and shorten the leach cycle to quickly get out of the valley bottom; at Barrick's Pierina gold mine, also in Peru, the first two lifts were nearly double the standard thickness and the leach cycle was reduced to 30 days.

Surface water management

One key problem is the generally steep terrain above VLPs. In many cases, the natural terrain above the pad will have areas greatly in excess of 45°, making construction of reliable diversion works difficult and expensive. Even when the channels can be constructed, such steep natural terrain is prone to local landslides and debris flows, rendering diversion unreliable. It is, therefore, common to consider the entire catchment area for purposes of determing extreme event flows.

With most conventional pads, surface water concerns start small and escalate with time, allowing operations to sort out the numerous other issues that arise during construction and commissioning. Not so with a VLP. Since the initial pad area is in the lowest part of the valley, surface water management becomes critical even before earthworks construction commences.

Closure

This is perhaps the most important and under-addressed problem with impounding heaps. These facilities have two unique features requiring special attention in closure planning: highly variable ore depths and the internal impoundment.

As ore depths vary, so does the time required to properly rinse the leached ore to regulatory limits, which is generally based on effluent water quality but sometimes also based on residual chemistry in the heap. The deepest areas will dictate the total rinsing time required. This is made more complex by the general lack of hydraulic separation in VLPs, which means that none of the heap is fully neutralized until it all is rinsed. This then precludes, for most practical purposes, the very desirable practice of sequential heap closure and the release of related financial sureties.

To ensure long-term physical stability as well as to allow proper neutralization of the bottom of the heap, the internal pond much be breached. The simplest method is to simply perforate the liner system with a series of drill holes, but these are not particularly reliable. In all but the more arid sites, breaching the dam will be required. But, since the upstream face of the dam is buried with leach ore, this can be a daunting task. These sites will likely compromise with a partial breach of the dam and perforation of the liner system. In Pierina's case in northern Peru, the dam is too large to fully breach, with 50 m (164 ft) vertically between the crest and upstream toe. Thus, the plan is to partially breach the dam and perforate the liner. To improve the performance of the perforations, an under-drain was installed beneath the pump caissons as a "drill target." That is, the head of the drain was made large enough to be reliably intercepted by multiple drill holes. This was enhanced by the pump caissons acting as drill guides and then, after closure, as infiltration galleries. Time will tell how reliable this approach proves to be.

Conclusions

This comparison of impounding valley leach pads to fully drained heaps indicates that, in most cases, drained heaps are lower risk to the environment and the most economical for construction, operations and closure. The highest risk factors for VLPs are liner leaks that are nonrepairable due to stacking conditions and the potential risk of internal pond submerged ore liquefaction in high seismicity regions. (References are available from the authors.) ■