Investigation of a Heap Leach Facility leak using Finite Element Seepage Analysis

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Abstract

Gold heap leach facilities (HLFs) are susceptible to environmental releases of gold-cyanide pregnant leach solution (PLS) if deformities and perforations in the engineered liner systems occur. This case study presents how the two-dimensional, finite-element, variably saturated seepage modeling program, SEEP/W, predicted PLS fate and transport. Results demonstrated PLS does not reach a groundwater well downgradient of an HLF even after increasing leakage rates and 30 years of post-heap closure. These results helped regulators develop a response and management plan and demonstrated the importance of fate and transport modeling when HLF leaks occur.

Keywords: Cyanide, fate and transport, unsaturated hydrogeology.

Introduction

Cyanide leaching through HLFs is a widely applied method for recovering gold from oxide ore (Hiskey 1985). HLFs are engineered to collect and transport any and all PLS from the heap to the processing facility. A standard leachate collection system (LCS) consists of four layers (Lupo 2010):

1. The over liner, boulder to cobble-sized material which collects PLS and protects underlying leachate collection pipes from stacked ore;
2. The composite liner, high-density polyethylene (HDPE) or similar material which is an impermeable layer for PLS to accumulate atop while it is collected by the leachate collection pipe system;
3. The under liner, engineered low-conductivity clay layer (LCCL), compacted to a hydraulic conductivity of approximately 1×10^{-6} cm/s, provides a final barrier to protect any PLS from percolating into the substrate; and,
4. The leak detection system (LDS), consisting of perforated drainpipes, monitors for any PLS that may flow through the LCCL and into the environment.

During LCS installation and subsequent additions of ore, it is common for deformities and perforations to exist throughout the LCS or, more specifically, the composite liner (Rowe *et al.* 2013). If these failures expand to great enough size or occurrence, the LDS will start to detect PLS leakage.

Different jurisdictions have varying leakage rates of PLS that are not considered a hazardous release into the environment. For example, one jurisdiction in the United States reports 25 gallons/day (94.64 L/d) as the actionable limit.

For this case study, an HLF in a confidential location detected a leakage rate in two HLF leaching cells that were above the actionable limit. However, due to the placement of the LDS at this HLF, which was installed *above* the LCCL (it is typically installed below the LCCL), this leakage rate did not necessarily equate to a release to the environment. Ultimately, the HLF owners needed to know the risk of environmental contamination from the liner breach. Therefore, a predictive seepage analysis of the fluid dynamics of the PLS through the HLF, the LCS, and the underlying substrate was executed.

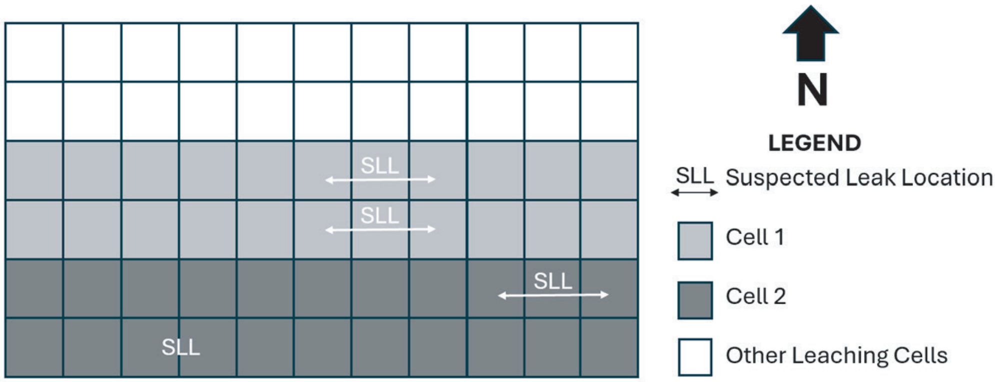

Figure 1 *Overhead HLF Grid with Cell 1 and Cell 2 Suspected Leak Locations.*

Methods

Leak Detection

Before the seepage analysis could be performed, the location of the leak had to be determined. Using historical leach application records, and historic PLS collection results for different HLF cells, many arrays were created in Microsoft Excel to model when different sections of each cell were actively leached. The approximate location of the leak for each leaching cell (Fig. 1) was ascertained using the Excel arrays with leachate application time-series records and LDS leachate collection rate observations. Most notably, the Cell 1 leakage rates and application schedules suggested only one central location for the leak while Cell 2 suggested one to two major leak locations.

The locations of the leaks, and their magnitude, was considered in all future modelling and mitigation evaluations.

Conceptual Model

Since the detected leaks were found to occur in horizontally adjacent cells, and because the gradient is consistently vertical within the vadose zone, and to one compass direction in the saturated zone, 2D cross-sections can be used to conceptualize the leak mobility during and between phases of the HLF. The HLF evaluation considered three phases of operation: the current configuration (under leach), ultimate configuration (with more ore, and also leached), and closure (capped without leaching.) (Fig. 2). The mine does not anticipate placing much more ore on this area of the HLF. As a result, the ultimate configuration of the HLF will occur several months after the current configuration. If operations were to continue as planned, the closure (capped) configuration would occur two years after the end of ore placement and residual leaching.

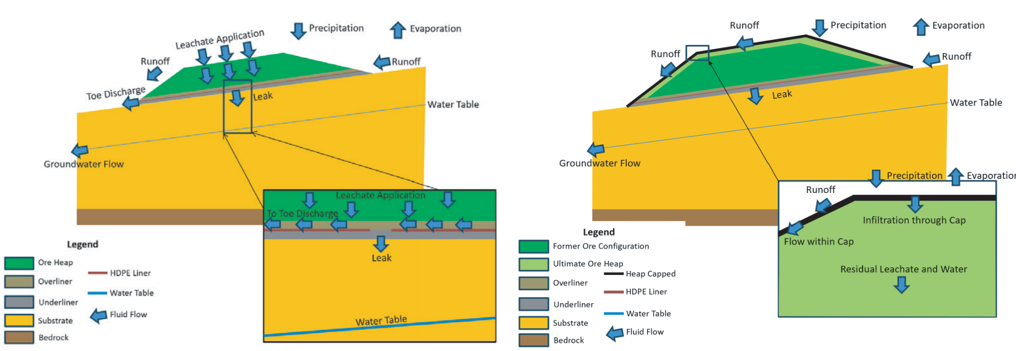

Figure 2 *Conceptual Models of the Current Configuration (left) and Closure (Capped) Configuration of the HLF (right).*

During operations, the greatest amount of fluid flow travels through the ore into the LCS to the toe discharge, which delivers PLS directly to the processing facility. Only a small fraction of the fluid flows through the breach in the liner. This is because there is a several order-of-magnitude difference between the over liner next to the leachate collection pipes (1×10^{-2} cm/s) and the LCCL below the liner (1×10^{-6} cm/s).

After a short period where new ore is stacked and leached, the HLF has a two-year period of residual PLS leaching to extract more gold. Finally, the HLF leaching ceases, and the amount of fluid flowing through the HLF decreases exponentially as the ore drains out. Post-leaching and after drain-down, there is no longer PLS sitting atop the leak. This results in an exponential decrease in the PLS moving through the breach in the liner.

Potential mitigation measures were also considered. It is possible to install an inter-lift liner prior to the ultimate configuration of the HLF (Fig. 2) to divert the flow of PLS applied to the heap away from the breach and towards the LCS. In this conceptual layout (Fig. 3), only residual leachate stored in Cell 2 encounters the liner breach because PLS above Cell 2 is diverted horizontally by the inter-lift liner. The inter-lift liner concept does not consider stability and structural integrity of the HLF, which must be evaluated separately before it can be applied to the HLF.

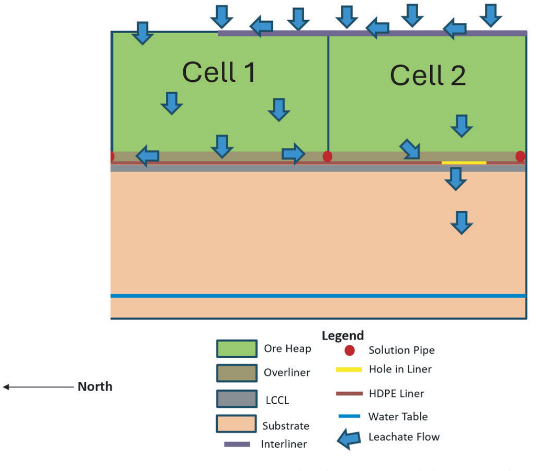

Figure 3 Conceptual Model of an Inter-lift Liner for Cell 2.

This mitigation measure was presented to the client as a solution (if required) to lower the potential release of PLS to substrate.

Predictive Groundwater Model

To conduct the seepage analyses, the two-dimensional, finite-element, variably saturated seepage modeling program SEEP/W was chosen because it is capable of assessing the non-linear dynamics of unsaturated groundwater flow through steady-state and transient state analyses (GEO-SLOPE International Ltd. 2015). The program uses a mesh of nodes to quantify the flow dynamics of water within the model domain. Additionally, a two-dimensional model is sufficient for this case study due to the direction of flow being either vertical (to the water table) or downgradient towards the toe of the heap.

To construct the model, several features needed to be implemented into the program. These included HLF and geologic cross-sections, material properties, finite-element mesh for each material, and boundary conditions (BCs). Geologic cross-sections of the HLF foundation were acquired from previous geotechnical studies and monitoring wells drilled around the HLF. The HLF cross-section was acquired from HLF as-built drawings.

Properties for the unsaturated and saturated materials were based on soil water characteristic curves (SWCCs) and hydraulic conductivity values (K-values) derived from lab-analyzed samples of the materials used in the heap (ore) and the LCS (unconsolidated cobble over liner and clay under liner). Substrate properties were assumed based on core samples analyzed during drilling of monitoring wells (silty sand with gravel) with a porosity value of 0.25 (Heath 1983) and a K-value 6.8×10^{-4} cm/s (Domenico and Schwartz 1990). These materials were then assigned to different regions in the model according to layers presented in the conceptual models.

Once each material was incorporated into the model, an appropriate finite-element mesh was applied to each region. A finite-element mesh is used in SEEP/W to calculate fluid and mass transfer within each region.

Finer meshes result in longer run times, but more refined results especially for modeled locations of concern. Focusing on the breaches in the liner, a coarse mesh was assigned to parts of each region that were outside the breach, while a fine mesh was assigned to the over liner, LCCL, and substrate regions near the liner breach.

Several BCs were implemented to simulate PLS application and PLS collection. The leachate application rate of 2.7×10^{-6} $m^3/s/m^2$ was directly reported by the HLF owners, while precipitation (applied to the heap when leachate application was "turned off") was calculated based on the average yearly precipitation. Because the HLF is in an arid region, precipitation is not a significant factor. A 10% infiltration rate was chosen during current and ultimate heap configurations, while a 1% infiltration rate was chosen for the closure (capped) configuration. PLS collection pipes were zero pressure boundaries, which would cause any PLS to preferentially flow towards these collection points. Hydraulic head boundaries were defined from monitoring wells located upgradient and downgradient of the HLF. The difference between these boundaries generated a water table oriented properly with the HLF and other material geometries.

Steady-state calibration was performed to a "snapshot" of HLF operations, but the steady state model was not relevant to the results. The transient model contains the following time steps:

- Ore loading and active leaching (day 1 to day 1048);
- Active leaching in the ultimate configuration (day 1049 to day 1778);
- Residual drain down, calibrated to state-approved HLF drain down model (day 1779 to day 3603);
- Uncovered (day 1 through day 1778) with 10% precipitation infiltration;
- Covered (day 1779 through day 12728) with effectively zero infiltration.

Using this time series, historic and future PLS fate and transport was simulated.

Results

Flow Modeling of the Leak

Initial results of the transient models for the Cell 1 leak show moisture migration is clearly visible under the HDPE liner in the area of the breach. A modeled pressure head of 0.38 m above the liner and breach is also observed (Fig. 4).

However, the moisture does not significantly penetrate the Cell 1 LCCL, even after two years of PLS application. This is because (as mentioned above) the LCCL is specifically compacted and conditioned to be a secondary backup liner to the HDPE. The results show that even the substrate, despite the fact that it contains coarse-grained material, acts as an impediment to PLS flow. Under vadose zone flow physics, dry materials have a lower conductivity than wet materials often by several orders of magnitude (Brady 1990). The leak from the Cell 1 HDPE breach going through the LCCL does not have enough moisture to "wet" the substrate to a point where it augments the hydraulic conductivity. This causes the moisture front to stay stored in the LCCL and upper substrate.

For Cell 2, which had a larger breach in the liner, there is a much greater PLS plume in the substrate (Fig. 5).

Upon reception of these results, the HLF owners requested several sensitivity analyses be simulated to minimize any Cell 2 PLS release into the environment. These included cessation of leaching activities two years after

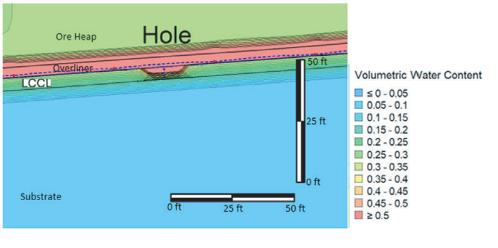

***Figure 4** Moisture and Particle Tracking from Cell 1 after 2 years of Leak Detection. The blue dashed line above the LCCL is the hydraulic head above the liner.*

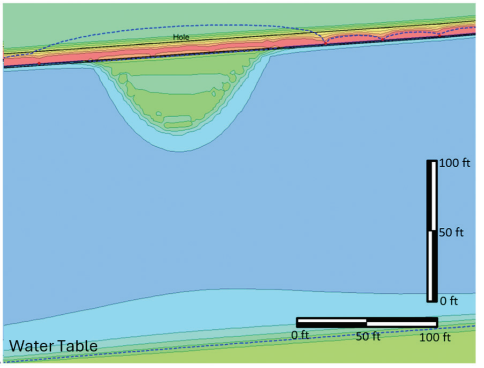

Figure 5 *Moisture Tracking from Cell 2 after 2 years of Leak Detection.*

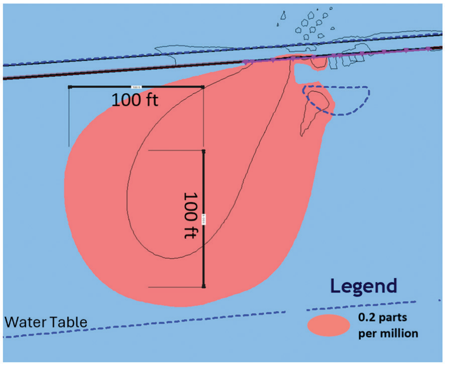

Figure 6 *PLS plume extent, 30 years after Closure Configuration.*

the leak was detected and the application of an inter-liner. The most-reasonable mitigation was a shorter PLS application time even though this resulted in some loss of gold recovery. According to the model, approximately 2260 L of residual leachate remains in the HLF after 10 years of drain down.

Chemical Fate and Transport Modeling

Considering the results presented in Fig. 5, additional contaminant fate and transport modeling was simulated to ensure PLS did not reach the water table below the LCS. The chosen program was CTRAN/W, a finite-element program for simulating the transport of a dissolved constituent or gas through porous media by advection and diffusion. The model also includes a half-life for cyanide degradation of one year. This half-life is representative of cyanide degradation in the atmosphere (Razanamahandry *et al.* 2017). Since the vadose zone is mostly composed of air and not water, the environment for the fate and transport of the PLS plume reflects atmospheric conditions.

A 0.2 parts per million minimum concentration plume was then simulated in CTRAN/W. This minimum value was selected as the United States national drinking water standard is 0.2 parts per million (Agency for Toxic Substances and Disease Registry 2006). A minimum concentration plume refers to a plume with the extent set to a minimum concentration value. Thus, anything inside the plume is greater than the extent (red, Fig. 6) while everything outside the plume is set to 0 parts per million (blue, Fig. 6). Results from the model indicate that 30 years after the closure configuration, the plume would not reach the water table and is about 229 meters away from the toe of the HLF (Fig. 6).

Conclusions and Discussion

Upon presentation of the flow plus fate and transport modeling results to the regulators, the mine formulated an action plan, consisting of monitored natural attenuation which involved the observation of changes to water quality from monitoring wells downgradient of the HLF.

The results show that, even though liner breaches may occur, heap leach facilities are designed and constructed to mitigate PLS release with a multiple-tier protection system. In this case, the HDPE liner and the LCCL work together to mitigate environmental release, even when an HDPE breach occurs.

This case study showed that it is possible to detect the location of the leak from the leaching history, and to simulate the effects of a liner breach on the transport and fate of PLS. The driving factor in the result was the engineered low conductivity of the LCCL (compacted and tested to < 1×10^{-6} cm/s) and the power the unsaturated zone and relative permeability function combined with a low flux rate into the substrate to mitigate long-term PLS transport.

Acknowledgements

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