Evapotranspiration Caps for Mine Waste Closure – Case Studies in Extreme Environments

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Abstract Evapotranspiration Caps (ET Caps) for barren rock disposal facilities (BRDFs) and other mine waste structures offer an affordable cover alternative for mine closure that can greatly reduce the quantity of leachate and the impact that mine waste has on the environment. ET Caps are designed for the site-specific soil, vegetation, and climate conditions to minimize infiltration. Variably-saturated groundwater models effectively predict the performance of ET caps to optimize the design. This paper presents two extreme studies for ET caps– one in the jungle of Venezuela and another in the Sonora desert of Mexico.

Key Words Evapotranspiration caps, mine waste, closure, leachate

Introduction

Two mining gold projects, the Brisas del Cuyuni Project (Brisas Project) in Venezuela, and the Santa Elena Project (Santa Elena Project) in Sonora Mexico, are expected to produce significant quantities of barren rock during operations. This barren rock will be placed in a BRDF and has the potential to produce leachate water quality that will not conform to regulatory guidelines. In response to this environmental risk, both sites are expected to utilize an ET Cap to mitigate the quality and quantity of leachate that will drain out the base of the BRDF. ET Caps are effective waste covers that have been accepted by the U.S. Environmental Protection Agency for the capping of industrial, mining, and municipal wastes and can be an effective alternative to plastic (HDPE) and compacted clay covers (Benson, et. al, 2001). The ET Cap design must be optimized based on the following factors:

- Available soil;
- Barren rock and soil unsaturated and saturated flow properties;
- Site climate; and
- BRDF structure and design.

The mine waste facilities in these projects are large engineered mine waste structures. The Brisas Project will have 1.2 billion tons of waste rock stored in two separate waste rock facilities with a design that includes clay encapsulation of potentially acid generating (PAG) rock. The Santa Elena Project will have 30 million tons of waste rock stored in a single facility. The closure plan for both BRDFs is to cap them with cover soil and revegetate them with native plants. However, the clients have chosen to use engineered ET Caps that are designed to be protective of the environment with a goal of eliminating the need for perpetual water treatment.

This paper discusses the results of the ET Cap optimization studies, and how these studies were incorporated into the mine closure plan and environmental permitting documents. ET Cap optimization studies require an analysis of unsaturated flow conditions where the conductivity of a porous material is a function of the moisture content and the saturated conductivity according to the following equation:

$$q = -K(\theta)\nabla H$$

Where:

- q = groundwater velocity (L/t)
- $K(\vartheta)$ = hydraulic conductivity as a function of soil (or rock) moisture content (L/t); and
- H is the hydraulic gradient (L/L; from Tindall and Kunkel 1999).

The equation above creates a system of non-linear equations that must be solved to predict groundwater flow and the solution is therefore best resolved with modern computer modeling techniques.

Methods

Both projects began with a field data collection program. Data collected included the following categories:

- Aquifer properties: (single and multiple well aquifer testing);
- Climate data: (Evaporation, plant transpiration, precipitation, storm hydrographs);
- Soil properties: (Gradation, texture, saturated conductivity, and a soil-water characteristic curve);

Aquifer properties were collected from single wells and from aquifer tests. At both projects the water table was below the bottom of the BRDF. Saturated-zone aquifer analysis was used only in leachate mixing and water quality impact calculations.

Detailed climate data is essential to the studies. Average precipitation and estimated evaporation do not provide sufficient detail to simulate how climate factors impact soil moisture over time. Detailed storm hydrographs and carefully measured climate parameters are essential inputs to an ET Cap optimization model.

Soil properties are critical to the ET Cap studies because the unsaturated flow properties of the cover soil and the mine waste are the most important single factor in determining the ET cap efficiencey and design. A particle size distribution (PSD) analysis is followed by a Soil Water Characteristic Curve (SWCC) analysis in order to characterize the unsaturated flow dynamics of the soil or rock. SWCCs characterize the power of matric suction forces in a soil at various moisture contents and are a key input to deriving the $K(\vartheta)$ function shown above.

In addition, GRE personnel worked with mining engineers to determine the BRDF design parameters, and the mining and economic limitations that the ET Cap must be designed under. Becasue these facilites are so large, small changes in the closure and managment strategy can have massive impacts on the final cost of the project. It is therefore essential that enviromental engineers work with mining engineers and geotechnical engineers to determine the feasible design parameters for each project.

Groundwater models capable of simulating saturated and unsaturated conditions offer engineers an opportunity to test different designs to determine the efficacy prior to construction. The U.S. EPA requires groundwater modeling or similar analysis to prove that an ET Cover is "equivalent" to clay or HDPE Covers (EPA 2003). For both of these projects, Vadose/W (Krahn, J. 2007), a two-dimensional variably saturated finite element groundwater flow model was selected due to its rigorous simulation of unsaturated flow and rainfall events, as well as its ability to integrate with slope stability simulations. In the case of the Brisas project, the model results were verified with mass-balance soil test cells (Test Cells) and the results were used to evaluate the accuracy of the modeling efforts. (Hudson 2009).

Results: Arid Environments

In an arid environment, when potential evaporation greatly exceeds precipitation, (300 mm per year of precipitation, and greater than 2 meters per year of potential evaporation) ET Caps can be designed to be effectively "zero flow". They can be designed to meet or exceed the performance criteria of plastic HDPE covers, and can be engineered to last longer (Benson et. al 2002). The challenge for ET caps in an arid environment is designing the ET Cap such that the storage of the soil cover is sufficient to hold any potential infiltration until evaporation and plant transpiration can remove it. However, in Santa Elena's arid environment, where the vegetation is active during the wet season, and where there is no snowmelt or spring runoff, storage is less essential.

The SWCC of the Santa Elena mine waste greatly influenced the results of the modeling. Figure 1 shows the SWCC, and the moisture, conductivity curve.

One can see that the run-of-mine andesite waste has a very steep SWCC curve. This means that it loses nearly all of its moisture under free drainage, and the residual moisture in the material is very low. If one plots the "free drainage" moisture content (-33 kPa) onto the moisture-con-

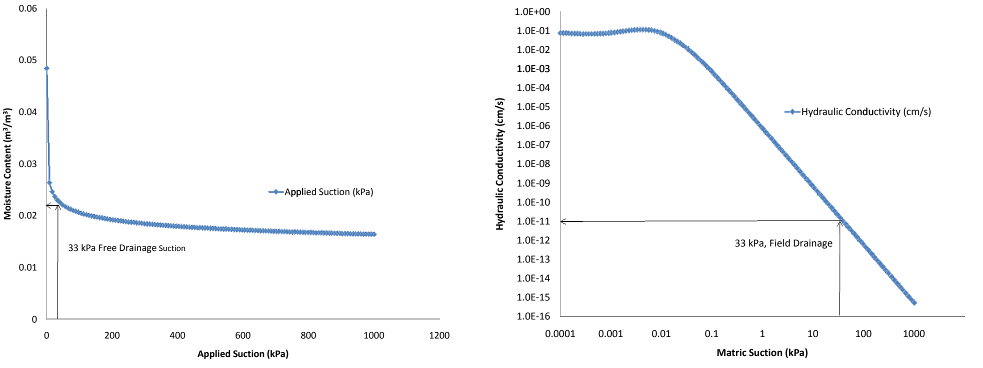

Figure 1 *SWCC and Moisture/ Conductivity Curve for Santa Elena Waste*

ductivity curve, one can see that the drained waste rock will generally have a very low hydraulic conductivity – on the order of 10^{-11} cm/s. Although counterintuitive, when dry, the coarse and gravelly waste rock at the Santa Elena mine is almost completely impermeable. This is due to the power of the capillary and adhesive forces on the surface of the dry rocks (Brady 1990).

This low conductivity, in conjunction with the high evaporation created a nearly impermeable ET Cap. Simulations predicted that in even a wet year, only one-tenth of one percent of annual precipitation makes it through the 30cm thick soil cover. These results were consistent with the findings of the EPA Alternative Cover Assessment Program for Arid Region ET Caps (Benson et. al. 2002). However, almost no seepage discharges out of the bottom of the BRDF. The unsaturated flow properties of the mine waste significantly improve the total hydraulic performance of the BRDF, and a "cover only" analysis of the system would not have been representative. Even in long term (200 year) simulations, the waste rock acted as a seemingly infinite sink for seepage water and a nearly impenetrable barrier to unsaturated flow.

Results: Tropical Environment

At the Brisas del Cuyuni Site, the tropical environment and 3.5 meters of annual precipitation made a zero flow cover impossible. Therefore, the goal was to minimize the quantity of BRDF leachate and to keep the cover moisture high to prevent the infiltration of oxygen. A compacted saprolite soil cover reduced the infiltration to thirteen percent of total infiltration, but the infiltration still created a large quantity of total leachate discharging into the environment.

Dual-phase groundwater and soil air flow modeling was performed to determine the total gas diffusion potential through the cap. The ET cover was optimized to retain a relatively high

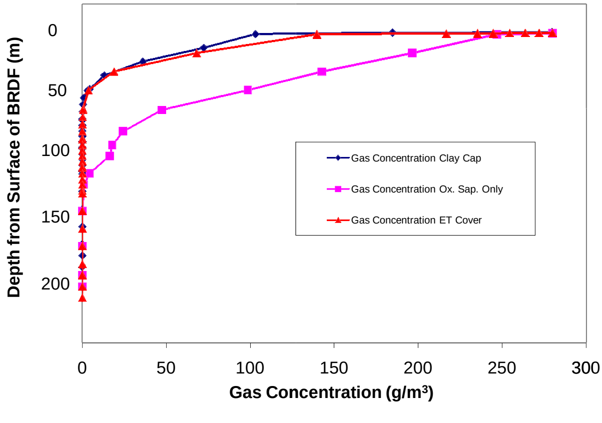

Figure 2 *Soil Gas Oxygen Concentrations versus BRDF Depth at the Brisas Project*

total moisture content while simultaneously minimizing precipitation infiltration. It was possible to meet these apparently contradictory objectives by iteration of the cover thickness to achieve the desired balance of infiltration/evapotranspiration. Results showed that the ET Cap (which included a capillary break and 1.0 meters of compacted saprolite soils) outperformed an uncompacted saprolite cover and closely matched the performance of a simulated 10^{-6} cm/s clay cap (see Figure 2).

Subsequent geochemical modeling predicted that this decrease in oxyen availability reduced the total acidity of leachate from apprximately 2000 mg/L $CaCO_3$ equivalent to approximately 200 mg/L $CaCO_3$ equivalent. This reduced acidity made passive treatment a feasible alternative (Breckenridge and Hudson, 2007).

Conclusions

Despite the drastically different environmental conditions of the two studied sites, ET Caps had significant advantages over other engineered mine waste closure strategies. At the arid Santa Elena mine, the ET Cap is predicted to effectively eliminate mine waste leachate with a 30 centimeter vegetated cover over the run-of-mine waste.

At the Brisas del Cuyuni Mine, the ET Cap sealed off oxygen diffusion and greatly slowed the kinetics of ARD-producing geochemical reactions. In both cases, the ET Cap design was accepted as an integral part of the mine waste management plan and closure plan by local regulators and lending institutions. The study results were incorporated into Mine Closure Plans (with Bonding Requirements), Environmental Impact Statements and/or Bankable Feasibility Studies.

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