Evapotranspiration Cover Design Optimization – A Case Study

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Abstract

Evapotranspiration (ET) covers are an industry-standard tool for mine waste leachate mitigation in arid and semi-arid climates. A new ET cover was designed, field-tested, and optimized with computer modeling for the tailings storage facility (TSF) at the Zangazeur Copper-Molybdenum Complex (ZCMC) in Kapan, Armenia. Collected field data from ET cover test cells, soil characteristics, and climate data were combined to create a variably saturated groundwater flow model which simulated the effectiveness of the new cover for over 10 years. The model was validated to the field-observed measurements of moisture. A minimum thickness of cover that would prevent breakthrough was recommended.

Keywords: Evapotranspiration cover, vadose zone groundwater modelling, closure cover

Introduction

The TSF at ZCMC is an upstream-raise TSF with a 5.7 km^2 exposed surface area in need of reclamation. Tailings impounded in the TSF are not acid-generating, but they do produce a leachate that is high in some regulated metals which has the potential to affect downstream water quality, and, therefore, must be managed to eliminate the mobilization of dissolved metals. The site receives an average of 550 mm of rain a year, making it a semi-arid environment that is suited for ET cover installation.

It is industry standard practice to mitigate metal leaching (ML) of mine tailings through the installation of an ET cover which is designed to absorb and store wet-season moisture. The cover is vegetated so that direct evaporation and plant transpiration can remove stored moisture during the dry season to prevent breakthrough (defined as infiltration through the cover into the tailings). Mining projects and the US Environmental Protection Agency (EPA) have shown that, if properly designed, ET covers can virtually eliminate infiltration of precipitation into lower layers of material in arid and semi-arid environments (Benson *et al.* 2002).

Much of the existing tailings dam face is covered with a reclamation soil cover. The original cover was designed in 1975 and relied on the use of a compact clay layer with low saturated hydraulic conductivity to prevent leachate into the tailings. From top to bottom, it consisted of 20 cm of topsoil and 50–70 cm of compacted clay.

Since the time of the cover's design, it has been shown that a compacted clay barrier placed directly atop of fine-grain waste often does not maintain its protective functionality, especially in arid or semi-arid environments (Bolen *et al.* 2001) (Albright *et al.* 2004) (Bonaparte *et al.* 2004). Repeated wetting and drying cycles in combination with root intrusion by vegetation can result in an increase in hydraulic conductivity up to two orders of magnitude (Maine Bureau of Remediation and Waste Management 1997) (Albrecht Benson 2001). As a result, ZCMC hired Global Resource Engineering (GRE) to update their original cover design to one with a coarse-grained capillary break layer that takes advantage of the difference in pore sizes at the boundary between the finer storage material and the coarser capillary break material to minimize the infiltration of stored moisture into the tails. While the cover with the capillary break may be negatively affected by root intrusion and subterranean fauna, this paper assumes that these elements will not affect the performance of the cover over time.

Field Programming

GRE designed a field program to confirm the necessity for a new ET cover, and to properly characterize available onsite material. Two instrumented ET cover test cells, 3 m by 3 m, were installed on the surface of the TSF to compare the efficacy of the existing and new cover design, and to gather in-field data on moisture changes throughout the cover soil profile. 3 m by 3 m was chosen due to its ease of construction and amount of instrumentation available. The test cells were installed as detailed in Fig. 1, with moisture sensors and lysimeters installed to monitor water infiltration and seepage through the two covers. GRE realized that pan lysimeters, even when fitted with diversion control collars and installed with a natural capillary break at the point where the pan collection occurs, could be inaccurate due to the formation of a zero-tension boundary layer within the soil that disrupts natural flow paths in unsaturated soils (Kahale *et al.* 2022). However, logistical constraints including long-lead times for fabrication and shipping limitations made a wicking lysimeter impossible to acquire prior to ground freezing in the winter.

The existing cover test pit was dug into the prior concurrent cover, with instruments placed horizontally within the cover to measure conditions with minimal disturbance. Installation of the soil lysimeter in the existing cover test pit was done by digging a pit adjacent to the test column area, then placing the lysimeter into a dug-out cavern at 120 cm below the layer of compacted clay and topsoil (Fig. 1). Before installation, an access port and hose were installed and checked, and the divergence control collar was backfilled with mine tailings. The remaining space around the lysimeter was backfilled with mine tailings. Moisture sensors were placed 80 cm and 120 cm below the ground surface in a similar fashion before backfilling the adjacent access pit with the same layers. Due to the way the instrumentation was installed, the vegetative cover remained undisturbed atop the test pit.

In the second test pit, a new cover was installed in accordance with the guidance for Engineered Covers within the Global Acid Rock Drainage Guide, with instruments placed within the cover during the installation process (INAP 2014). The pan lysimeter was placed in the center of the pit, 120 cm below ground surface, then backfilled with mine tailings (Fig. 1). Soil probes were installed at 150 cm, 110 cm, 70 cm, and 20 cm below ground surface by digging into the backfilled soil and placing the sensor at the proper location as planned in Fig. 1. Due to the design of the new cover, it was impossible to have undisturbed vegetation atop the new cover cell as was possible with the existing cover test cell. This difference was taken into consideration upon data analysis.

Measurements of the soil moisture content and soil temperature were taken twice daily from November 2022 to October 2023. Fig. 2 and 3 show the change in moisture

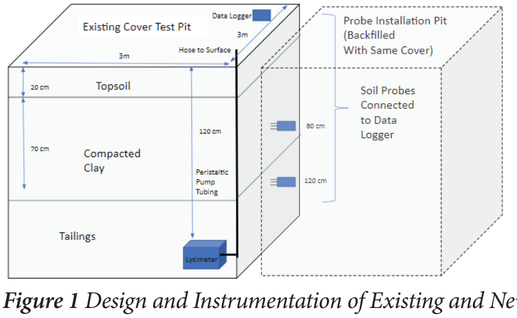

Figure 1 Design and Instrumentation of Existing and New Cover Test Cells.

content at the moisture probe locations in the existing cover test pit and the new cover test pit respectively. Both pits show an increase in soil moisture content in the upper layers of soil starting in early May, which is then followed by the wetting of deeper soil layers as water moves downward. There is an increase in moisture in the mine tailings in the new cover test pit, up to 0.25 m3/m3 (volumetric moisture content), but smaller in magnitude than the breakthrough event in the existing cover pit, which wetted up to 0.37 m3/m3. The soil moisture changes in the new cover test pit also represent an underperformance of the new cover, as it does not have established vegetation to further mitigate water infiltration.

The pan lysimeters installed in the test pits proved to be ineffective at collecting meaningful and accurate leached water volume for the two test pits, as the collected water volume did not correspond to the volumetric water content measured by the soil moisture probes. These pan lysimeters collected water from under the existing cover, but none under the new cover. As seen in Fig. 3, the surge in moisture seen in the capillary break and the mine tailings in mid-summer 2023 should have resulted in moisture collection in the new cover pan lysimeter, but none was measured. This disconnect between the moisture probe data and the pan lysimeter data remains a weak point in the study and will be discussed later in this paper.

Soil Characterization

For the construction of an ET cover, ZCMC must excavate and utilize soil and subsoil from the perimeter of the existing TSF. Because the area is large, and because different alluvial/colluvial materials are available around the TSF perimeter, a borrow material suitability study was conducted. 25 soil samples were taken from locations all over the site and included samples of topsoil, tailings, and other available material for use in the new cover. The samples were compacted to 80% standard proctor before testing, which is consistent with truck dumped and bladed material. All samples were sent to Lernametalurgiai Institute (LMI) geotechnical lab for analysis. LMI performed the gradation, compaction, hydraulic conductivity, plasticity, and moisture content tests of every sample. Additionally, the Soil Water Characteristic Curve (SWCC) (ATSM D6836-16 2016) was measured of 5 of the samples of the most-favorable borrow material.

The geotechnical and SWCC data was used to determine the range of soil types available onsite. The results show there are a variety of soils present on site, from very fine-grained clay to coarser grained sand and sandy gravel that would be suitable as borrow sources for topsoil, capillary break material,

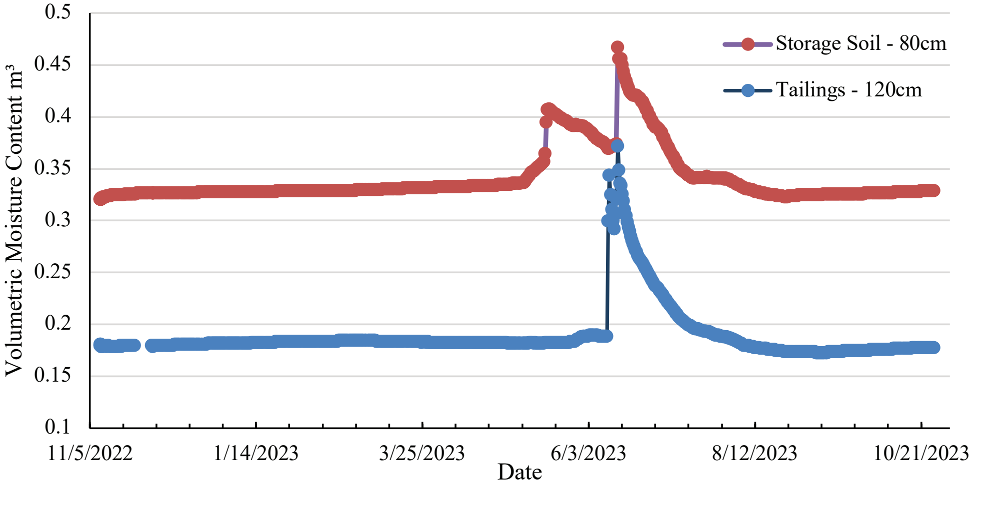

Figure 2 *Soil moisture changes in existing cover.*

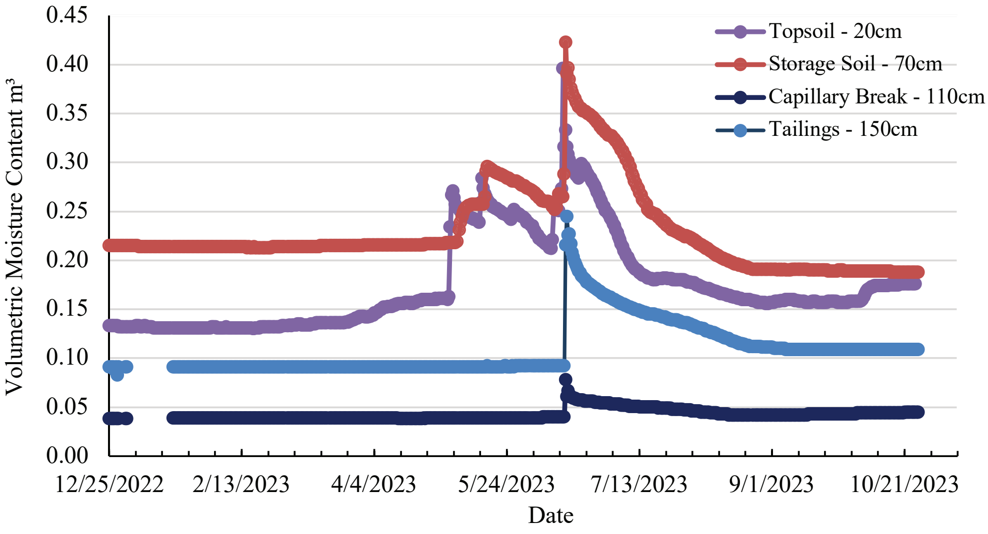

***Figure 3** Soil moisture changes in new cover.*

or storage soil. GRE determined that soil with between 45% and 80% of fine-grained material that passed through the 0.075 sieve, but still with a wide range of particle size that allowed for their hydraulic conductivity to be in the range of 10–5 –10–6 cm/s would be most suitable for use as storage soil.

Model Design

GRE created a computer simulation using GeoStudio's SEEP/W software which allows for the modeling of variably saturated groundwater flow and has a long history of application in the mining industry. The model can effectively simulate many years of climate effects on the cover, can elucidate the movement of water within the cover, and can be used to evaluate the viability of different thicknesses of ET covers. The computer model calculations are done using known scientific relationships of evaporation, transpiration, and soil-specific interactions with water.

2D column models of the existing and new cover were designed to be 1 m thick and 3 m wide to correspond to the dimensions of the two test cells and to minimize computing time. Soil layers within the model were created to replicate the corresponding new and existing ET cover designs.

Results of the onsite soil testing program were used to define materials within the model. The Van Genuchten equation was fitted to the SWCC lab results to produce a function that was representative over a wide range of soil matric pressures that would be present during the simulation. The SWCC for the remaining samples was estimated in GeoStudio using LMI-tested grain size data and liquid limits. The saturated water content of each soil was estimated based on each soil type (Heath 1983). Hydraulic conductivity functions were developed in GeoStudio using the preexisting SWCC functions and measured saturated hydraulic conductivity of each soil. The Fredlund-Xing-Huang estimation was used for clayey soils, and the Van Genuchten estimation was used for all other soils as is considered best in engineering practice (Zhang 2015). Thermal conductivities and volumetric heat capacity of soils are dependent on volumetric water content and were estimated based on soil type and measured water content.

The model is capable of simulating climate effects on water balance including solar radiation, precipitation, soil temperature, snowmelt, and transpiration. 10 years of daily precipitation, solar radiation, wind speed, and temperature data was provided by the meteorological station in Kapan, Armenia. This data was used to create a typical year, as well as a representative 90th percentile wet year for the site. 90th percentile wet year was selected to evaluate the impact of higher precipitation on the cover, but to not over-estimate future rainfall events. Additional climate and biological parameters necessary for the land-climate interaction function were filled in using available online data and site observations. It is important to note that the resulting average climate was representative of a typical year, and not specific to the 2022–2023 climate in the area.

Model Calibration

Collected in-field data from the installed soil moisture probes was used to calibrate the model. Discrepancies between the model-predicted data and the field data were noted and the model parameters were adjusted until the model represented empirical conditions as closely as possible while retaining fidelity to the lab testing and the climate data.

The model was able to predict the magnitude of soil moisture changes over time, but not the transient dynamics. Fig. 2 and 3 show a very rapid response to spring moisture that could not be easily duplicated in the model without substantial alteration of the material properties outside of the range of the tested values. GRE hypothesizes that the very rapid increase in moisture content measured by the probes may have been the result of preferential flow pathways, or a limitation of the modeling software to simulate a rapidly migrating moisture font traveling through the soil. The model is limited by the data that was available to GRE for input and calibration, as climate data was only available from one weather station and in-field soil moisture content measurements were only collected for one year.

Model Results

Despite the challenges in calibrating the model to the field data, GRE proceeded to simulate the new ET cover with a capillary break. The input geometry, material, and climate information were used by the GeoStudio software to calculate the climate effects on the existing and new ET covers over ten years. Single-particle tracking was also used to monitor the movement of a representative particle of water through the column and to track breakthrough through the ET cover into the tailings. The moisture content of locations within the model columns that coincided with locations of the in-field soil probes in the test pits were monitored. Additionally, the percentage of mass balance error in the simulation was monitored to have errors of less than 1% of the total water within the system.

The sample water balance, including the water balance error for the new cover, is shown in Fig. 4. Although the model could not be calibrated to match the in-field moisture probe data exactly, this was reconciled by the water balance data and the general moisture content patterns exhibited by the model system. Both the new and existing cover were designed to prevent breakthrough with repeated wet years (with 90th percentile rainfall). The total moisture infiltration and storage in the modeled cover was more than observed in the field.

Fig. 4 shows that the new ET cover can evaporate and transpire out all the moisture in the soil. The cover water volume increases with snowmelt in spring, but this moisture is then mitigated by evaporation and transpiration that both work to dry the soil and return it to the same water volume as at the beginning of the year. The simulation of the new cover shows near-zero vertical infiltration into the mine tailings and is predicted to function in a manner similar to the effectiveness of other capillary break covers (Benson *et al.* 2002).

Conclusion

Field instrumentation revealed that the existing cover on the site could be improved to meet the project goal of minimizing leachate and protecting groundwater quality. However, the study faced challenges in obtaining quality field data. The installed pan lysimeters did not comport with moisture content readings, and extremely rapid changes in moisture content observed in the installed moisture content probes could not be duplicated in groundwater models. For future studies, in place of of the pan lysimeters, wicking lysimeter should be installed, and a wider array of moisture content probes should be installed within both cover pits to be monitored for over a calendar year. However, a conservative model was built that demonstrated the effectiveness

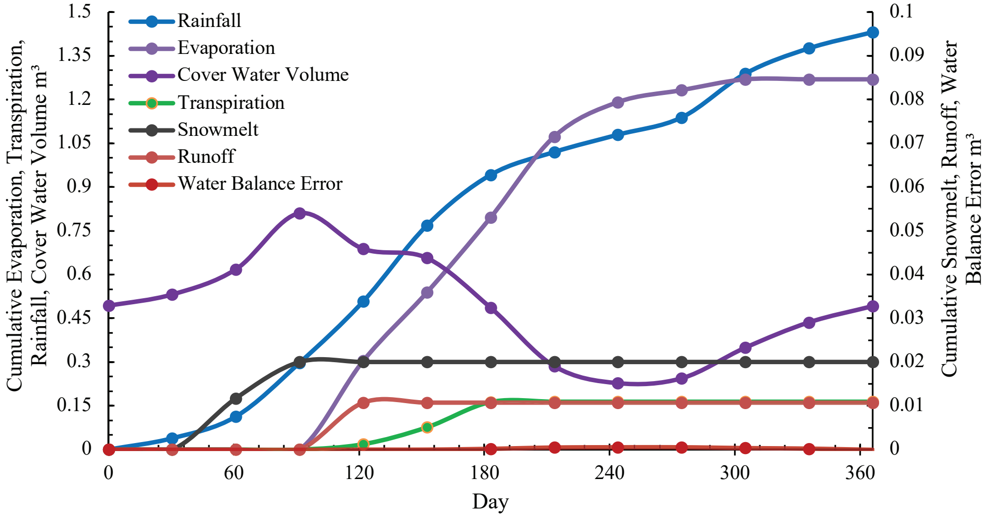

***Figure 4** Water balance in 0.5 m storage soil ET cover, year 10.*

of the new cover design at preventing leachate over 10 years. More work should be done to improve confidence in modeling results, as well as confirm this study's findings.

Despite these limitations, the study furthered the understanding of a best practice cover for the tailings facility. The ET cover model with the on-site borrow materials and the capillary break was robust, and it performed well with various material types and over a wide range of potential climate conditions. Switching to an industry-standard ET cover is part of ZCMC's continuing effort to achieve the ICMM international guidelines for concurrent and final mine closure (ICMM 2019).

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