Assessing the Reliability of an Unlined Tailings Storage Facility for Protecting Water Resources

Larry Breckenridge[1], Fred E. Bickford[2], Emily Luscz[3]

[1]Global Resource Engineering Ltd., 7000 South Yosemite St., Centennial, Colorado 80112,
lbreckenridge@global-resource-eng.com
[2]fbickford@global-resource-eng.com,[3]eluscz@global-resource-eng.com

Abstract Many regulatory agencies request lined Tailings Storage Facilities (TSFs) in hopes of better protecting groundwater resources. For the Corani Silver-Lead-Zinc project in Peru, lining the 160 Mt capacity TSF is not desirable. However, tailings solution containment is critical to meeting environmental requirements. To simulate containment of an unlined TSF, two models were used in tandem: a tailings consolidation model, and a groundwater flow model. The model results showed low-conductivity consolidated tailings seal the facility such that minimal seepage occurs. The modeling demonstrated that an unlined TSF can contain tailings solution equal to or better than a lined TSF.

Keywords Tailings, tailings consolidation, water resources, MODFLOW Surfact.

Introduction

The Corani epithermal silver-lead-zinc deposit in southeastern Peru will produce 160 Mt of mine tailings from its process plant over a projected mine life of 20 years. The project site is in the high Andes, 150 km southeast of Cusco, at an elevation of 5000 m above sea level (masl). The TSF will store conventional wet-tailings behind a 162 m high clay-core rock fill centerline-construction tailings dam. The TSF will require two saddle dams to reach the planned total capacity of 134 Mm^3 and will cover a footprint of 2.8 km^2. The impoundment falls in the Amazonian watershed, and is adjacent to several sensitive watersheds. As a result, the TSF must effectively contain tailings solutions, and must be protective of adjacent water resources over the long-term. Fig. 1 shows the TSF location and the location of the adjacent drainage basins.

Due to the projected size of the impoundment, covering the surface area of the TSF with an impermeable synthetic liner is not cost-effective, and despite state-of-the-art geochemical management practices, it is unlikely that seepage from the TSF will meet water quality guidelines. However, due to the physical properties of the tailings and the geologic properties of the TSF foundation, it is possible to achieve seepage containment without a liner.

To simulate the effectiveness of TSF solution containment, two models were constructed in tandem: a large-strain tailings consolidation model (FSConsol) and a MODFLOW-Surfact groundwater flow model (MODFLOW). The FSConsol model simulated the consolidation of the tailings and the ultimate conductivity of the tailings, and the MODFLOW model predicted the seepage from the dam and to adjacent watersheds.

Methods

Site Data

GRE conducted an extensive field investigation of the geologic conditions of the TSF. Approximately 3.2 km of boreholes were drilled under the dam, the saddle dams, and the impoundment. Packer tests as well as aquifer tests were performed in all borings to quantify the hydrogeologic properties of the TSF foundation. The investigation revealed that the impoundment is underlain by a lithic tuff that

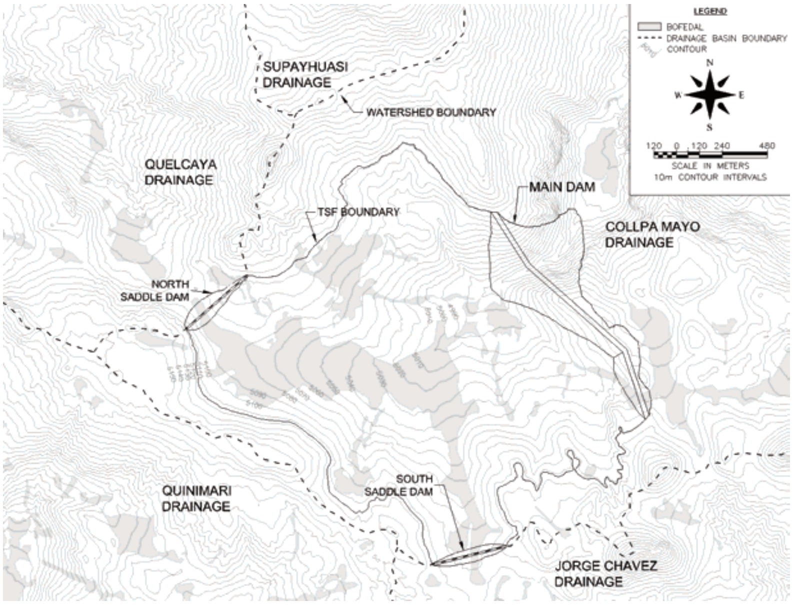

***Fig. 1** Location of TSF and adjacent drainage basins at the Corani Project*

contains very little primary or secondary conductivity. Isolated areas of fracturing were discovered in some boreholes, but these zones are not related to obvious geologic structures, and testing confirmed fracture zones are finite in extent and poorly connected to the surface water system. Unconsolidated sediments and bog-type organic soils (locally referred to as bofedal(es)) overlie the tuff in some portions of the TSF (Fig. 1). These bofedales host the shallow aquifer system in the TSF area. Apart from these shallow deposits which will be covered or excavated during construction, the TSF has a relatively impermeable foundation. The geomean of hydraulic conductivity from the 52 packer test intervals conducted in the TSF foundation rock is 4.6×10^{-6}cm/s.

Due to limitations in the amount of available clay, the TSF dam will be constructed with a dual material clay core with a 1×10^{-6} cm/s upstream core and a 5×10^{-5} cm/s downstream core. It has a chimney drain and a toe drain leachate collection system. The final dam also requires two saddle dams located adjacent to the Quelcaya and Jorge Chavez drainage basins (Fig. 1). The stage-mine life-volume relationship for filling the TSF was taken from the site operations plan (M3 2012).

In the latter half of mine life, the Corani project will install a pyrite flotation system to create a de-pyritized tailings product. The de-pyritized tailings will be created to minimize the risk of acid rock drainage (ARD) in the tailings impoundment. These de-pyritized tailings have a slightly different consolidation behavior than the tailings produced for the first half of the mine life. This difference is considered in the consolidation model and the TSF containment model.

Consolidation Model

Tailings that are deposited subaqueously consolidate under their own weight and under the weight of subsequent tailings deposition. This results in the densificationof the tailings, the creation of excess pore pressure, and a reduction in the hydraulic conductivity of the tailings over time.

The consolidation behavior was simulated using the software package FSConsol, a one-dimensional consolidation program based on finite strain consolidation theory. Finite strain consolidation theory is used to model scenarios which involve large strains and non-linear soil properties. FSConsol models simulate tailings consolidation using varying filling rates, varying pond areas, drainage conditions, and material types.

The consolidation model requires material properties relating to compressibility, permeability, and initial solid content for each material type.

The compressibility of the tailingsdetermines the relationship between void ratio (e) – defined as the ratio of the volume of voids to the volume of solids – and effective stress (σ') – defined as the stress transmitted through a soil mass less pore pressure. This relationship is expressed in FSConsol in the following form:

$$e = A\sigma'^{B} + M \qquad (1)$$

where A, B and M are constants.

FSConsol determines the hydraulic conductivity (k) as a function of the void ratio (e). This relationship is expressed in the following form:

$$k = Ce^{D} \qquad (2)$$

From these relationships, the FSConsol model can generate curves that relate the settling time, the tailings depth, and the conductivity of the tailings (GWP 2007).

Groundwater Flow Model

The Corani TSF was modeled using MODFLOW-Surfact (HGL 2010) and the Groundwater Vistas (Rumbaugh 2011) interface.

The steady-state version of the model was calibrated to water levels from the network of monitoring wells and vibrating wire piezometers installed during the field investigation. The calibration data set al. so included dry-season stream flow measurements, and average annual precipitation based on several years of records collected at the on-site automated weather station.

Simulating the filling of the TSF required simultaneous accounting of the changes in tailings depth, hydrostatic head, and hydraulic conductivity associated with the tailings deposition over time and space. Recent advances in MODFLOW code allow for the transient adjustment of hydrostatic head, and hydraulic conductivity, but the code does not allow for time-variant changes in model layer thickness. Therefore, the filling of the TSF was simulated through the General Head Boundary (GHB) boundary package. The filling of the TSF was simulated by adjusting the head on the boundary condition, and the consolidation of the tailings was simulated by adjusting the conductivity in the boundary condition. This method was applied at different values for different areas of the TSF under the assumption that the deeper portions filled faster and consolidated faster than the edges of the impoundment. Ten different boundary-condition zones resembling concentric rings were used to simulate the differential filling behavior over space and time. The result was a simulation that captured the complexity of the consolidation behavior over the footprint of the TSF.

The use of GHBs to simulate the tailings cannot simulate the drain-down of the consolidated tailings after closure because the tailings are a boundary condition, not an intrinsic part of the model with defined conductivity and storage. To overcome this issue, the TSF filling and consolidation was modeled for 30 years as a boundary condition to allow consolidation time to complete. Once consolidated, the model geometry was altered to make the tailings an active model layer with a thickness equal to the depth of deposited tailings, and with the properties of the fully-consolidated tailings. Using this method, the drain-down of the tailings could be simulated after TSF closure.

Results

Consolidation Model

Over time, the Corani tailings consolidate down to as low as 3.8×10^{-7} cm/s, but much of the de-pyritized tailings located in the upper portions of the impoundment will experience considerably less consolidation and will have a final conductivity of approximately 1×10^{-5} cm/s. This decreased consolidation is due to the shallower tailings depth in the upland areas of the TSF, and the nature of the depyritized tailings product. Fig. 2 shows an example of the tailings consolidation and permeability curve over time and tailings depth.

This complex consolidation behavior was integrated into the MODFLOW model of the tailings solution containment.

Groundwater Flow Model

Dam seepage was evaluated by the discharge into the toe drain boundary condition located beneath the downstream toe of the tailings dam (Fig. 3). The seepage behavior showed a linear increase in seepage with an exponential decrease to steady-state after closure. The discontinuity in the seepage line at year 10 reflects the change-over to de-pyritized tailings. The maximum seepage of ≈100 m^3/d (1.2 L/s) is modest for a 165 m high dam. Upon closure, the seepage rapidly decreases to 10 m^3/d (0.12 L/s).

The Quelcaya Basin (Fig. 1) showed no significant change in seepage resulting from the TSF. In fact, the stripping of bofedal sediments during the construction of the saddle dam results in a net decrease in seepage during mining operations. The Quinimari and Jorge Chavez basins see a slight increase in groundwater flow (10–20 %), but the change is not significant in comparison to the total water balance of the area, and as discussed below, does not generate from the TSF.

The project does not anticipate that the water quality of the tailings interstitial fluid will meet stringent water quality requirements due to elevated sulfate concentrations. As a result, Modpath (USGS 2000) simulations were used to determine the travel paths and travel time of any tailings fluid migration. The simulation showed that the TSF effectively captures all tailings seepage into the Collpa Mayo drainage under the tailings dam (Fig. 4). In addition, because the seepage must travel through the low-conductivity tailings and bedrock to escape the impoundment, travel times to the toe of the main dam are on the order of hundreds of years.

The total seepage of the TSF reaches a maximum of 219 m^3/d (2.5 L/s) just prior to closure. This modest seepage volume is the result of the consolidated tailings working in conjunction with the low-conductivity bedrock to prevent seepage from the tailings despite considerable hydrostatic head.

No liner system is perfect, and as a result, the US EPA has created liner seepage calculations and design guidelines to predict the seepage through a synthetic liner (Giroud & Badu-Twneboah 1992; Giroud & Bonaparte 1989; EPA 1992).The EPA techniques are analytical calculations that consider the typical frequency of small liner failures and the hydrostatic head present on holes in the liner, and extrapolate the potential seepage through lin-

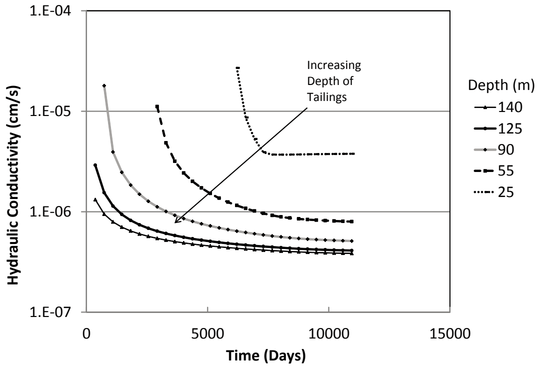

Fig. 2 *Changes in hydraulic conductivity over time at various depths in the TSF.*

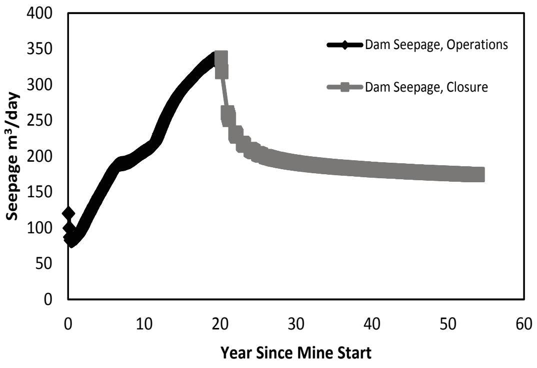

Fig. 3 *Model simulated dam seepage through time.*

ers covering large surface areas. This potential seepage was calculated for the Corani TSF and was compared to the MODFLOW predicted results. With all other assumptions identical to the MODFLOW model, the EPA liner seepage calculations predicted a total leakage from the TSF of ≈ 470 m^3/d.

Conclusions

For projects with fine-grained tailings, it is often the consolidation behavior of the tailings, and the final hydraulic conductivity, that determines the hydrogeologic behavior of the TSF. In the case of the Corani Project, large-strain consolidation testing and simulation indicate that the tailings would consolidate to a conductivity as low as 3.8×10^{-7} cm/s. This low conductivity consolidated tailing product, in conjunction with a competent-rock TSF foundation, produces a very low predicted total seepage despite the size and depth of the TSF. As a result the TSF has modest seepage to the dam toe drain (where it can be managed if required), and no significant seepage to adjacent drainage basins. In addition, particle tracking demonstrated that the TSF successfully contains tailings solution by channeling all potential seepage to the toe drain of the dam where it can be monitored and managed.

When compared to a synthetic liner, the unlined TSF has less than half the leakage estimated from a simulated lined facility. As a result, installing a synthetically-lined TSF foundation would result in no significant improvement in environmental protection despite the great expense.

This project provides an example to mining companies and regulators that unlined tailings storage facilities are not necessarily a threat to water resources even in cases when

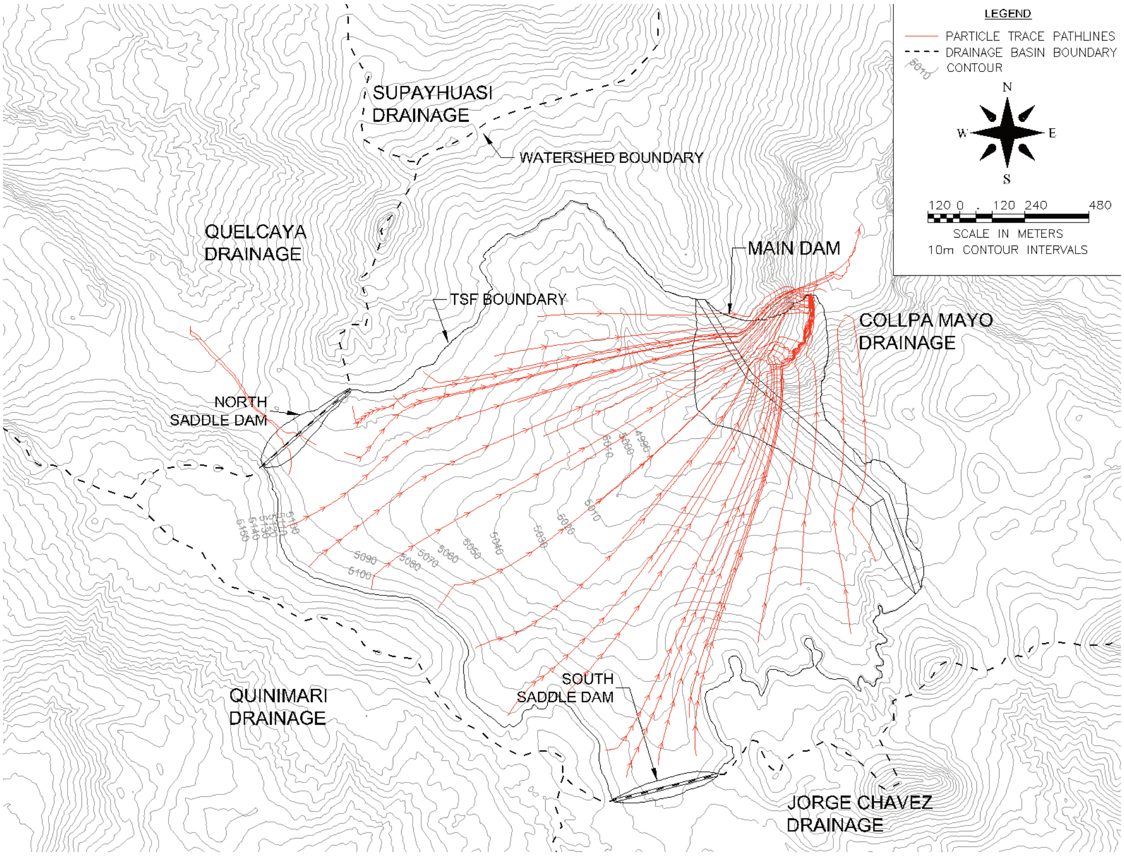

Fig. 4 Model simulated flow paths of tailings fluid within the TSF.

the interstitial water quality within the tailings may not meet regulatory requirements.

Acknowledgements

The authors thank Bear Creek Mining Company for permitting the results of the study to be presented at the IMWA 2013 conference.

References

EPA (1992) Action Leakage Rates for Leak Detection Systems-Supplemental Background Document for the Final Double Liners Leak Detection Systems Rule for Hazardous Waste Landfills, Waste Piles, and Surface Impoundments. V EPA 530-R-92-004, PB92-128214. U.S. Environmental Protection Agency, Office of Solid Waste.

Giroud J, Badu-Twneboah K (1992) Rate of Leakage through Composite Liner due to Geomembrane Defects. Geotextiles and Geomembranes, 11, 1–28.

Giroud J, Bonaparte R (1989) Leakage through liners constructed with geomembranes — Part II: composite liners. Geotextiles and Geomembranes, 71–111.

GWP (2007) FS Consol Slurry Consoliation Software, Version 3. Edmonton, Alberta, CA: GWP Software Inc.

HGL (2010) MODFLOW-Surfact. HydroGeoLogic.

M3 (2012) NI 43–101 Report on the Corani Project. Tuscon, Arizona: M3 Engineering.

Rumbaugh J (2012) Groundwater Vistas Version 6.29. Environmental Simulations.

USGS (2000) MODPATH particle trackign postprocessing model for MODFLOW. Reston, VA: United States Geological Survey.