

HYDROGEOLOGICAL ASSESSMENT OF SEEPAGE THROUGH THE ANTAMINA TAILINGS DAM – ANTAMINA COPPER/ZINC MINE, PERU, SOUTH AMERICA

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ABSTRACT

The Antamina copper/zinc mine in northern Peru is expected to produce about 750 million tonnes of tailings during the mine life. A tailings dam is being progressively constructed at the confluence of two valleys in order to retain these tailings. The tailings dam will be raised in stages, reaching a potential maximum height of around 240 m. Antamina is also considering, at a conceptual level, the potential for additional raises of the dam to a height of about 285 m. To assess future seepage through the dam and bedrock abutments, a three dimensional hydrogeologic model of the study area was constructed using FEFLOW, a three-dimensional finite element numerical code. The model incorporated available geologic data, results of hydrogeologic testing, and details of various dam components and other engineered structures. Following construction, the model was successfully calibrated to measured dam seepage, tunnel inflow, and hydraulic heads measured in the dam abutments and in the tailings. Future dam seepage was then predicted for the operation and post closure periods. The assessment considered large contrasts in hydraulic conductivity (e.g. dam rockfill vs. underlying bedrock), unsaturated conditions that exist in portions of the tailings and in the dam, complex hydrostratigraphy associated with steeply dipping bedrock units, the presence of tunnels under the right abutment, and changes in the location and extent of the tailings pond, tailings, and the dam throughout the mine life. Overall, long term estimates of seepage were found to be most sensitive to the hydraulic conductivity of the tailings and to the width of the tailings beach, and less sensitive to the hydraulic properties of the dam and bedrock.

1. INTRODUCTION

The Antamina copper/zinc mine in northern Peru is expected to produce about 750 million tonnes of tailings during the mine life. A tailings dam is being progressively constructed at the confluence of two valleys in order to retain these tailings. The tailings dam is situated within an interbedded sequence of folded Upper Cretaceous sedimentary bedrock consisting of limestone and mudstone. Structural features are present in the bedrock units including bedding-parallel structures, a suite of downstream dipping back-thrusts, major jointing trends, and karstic features. Figure 1 presents the general layout of the Antamina tailings impoundment.

The tailings dam and tailings basin have been in continuous development since 2000. The tailings dam will be raised in stages, reaching a potential maximum height of around 240 m, with a crest elevation of 4120 m. Antamina is considering, at a conceptual level, the potential of additional raises to heights of up to about 285 m, with a crest elevation of up to 4165. Considering the dimensions of the tailings dam and tailings basin relative to the valley, both structures exert significant influence on the groundwater regime near the dam. Seepage through the dam is collected in a seepage collection system at the downstream shell of the dam. This system intercepts seepage from several sources including: seepage from the tailings; groundwater seepage from the bedrock valley, natural groundwater flows from springs that discharge into the dam, groundwater inflow to a constructed diversion tunnel on the right abutment, and direct precipitation that falls on the downstream shell of the dam and runoff from the natural watershed above the downstream shell of the dam.

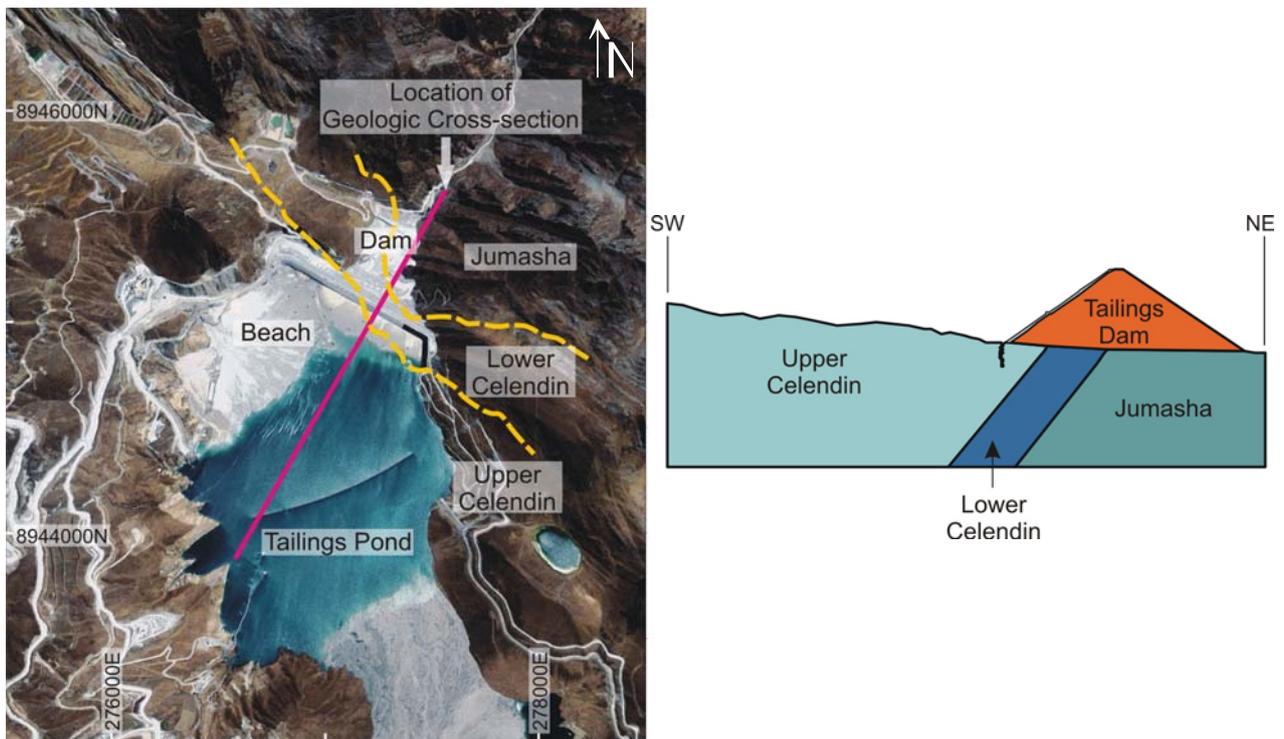


Figure 1. Antamina Tailings Impoundment and Representative Cross-Section

To assess future seepage through the dam and bedrock abutments during mine operation and post closure, a three dimensional hydrogeologic model of the study area was constructed using FEFLOW, a finite element numerical code (Diersch, 2003). The model incorporated available geologic data, results of hydrogeologic testing, and details of various dam components and other engineered structures. FEFLOW was selected for this project as it is capable of representing tunnels and other underground openings using discrete feature elements, it can simulate unsaturated conditions, and it can simulate temporal changes in boundary conditions and model input parameters during a single simulation run thus allowing for efficient representation of changes in the extent of engineered structures through the mine life. The hydrogeologic model was calibrated to past dry-season hydrogeologic conditions for six pond elevation stages.

2. CONCEPTUAL MODEL

A conceptual model was developed for the study area to support the construction of the numerical hydrogeological model. The conceptual model is a simplified representation of the groundwater regime that organizes and simplifies the hydrogeology. It must retain enough complexity so that the numerical model developed from it adequately reproduces or simulates the real groundwater flow behavior. Components of the conceptual model are described below.

Hydrostratigraphic Units

The sedimentary bedrock was subdivided into three principal hydrostratigraphic units: the Upper Celendin formation (greater than 75% shale and less than 25% limestone); the Lower Celendin Formation (less than 25% shale and greater than 75% limestone); and the Jumasha Formation (primarily limestone). The inferred surface expressions of these formations within the dam footprint (based on geological mapping and borehole investigations) are shown on Figure 1. Nearly 400 hydraulic tests have been conducted in the dam abutments to estimate the hydraulic conductivity of the bedrock units. In general the upper 50 m of bedrock appears to have a somewhat higher hydraulic conductivity than bedrock at greater depth, likely as a result of enhance fracturing throughout the upper zone of the rock mass. Overall, bedrock near the dam abutments has an average hydraulic conductivity on the order of 10^{-7} m/s to 10^{-6} m/s, suggesting moderate to low ability to transmit groundwater.

Tailings Dam, Tailings Basin and Tunnels

In the conceptual model the dam was simplified into several components, each of which may affect the rate of seepage through the dam and bedrock abutments (see Figure 2). These features included: a concrete face that was installed against the upstream face of the starter dam to an elevation of 4015 m; a geomembrane liner that was placed over a portion of the tailings beach at an elevation of 4042 m and against the dam face above 4042 m; three zones of engineered filter material against the dam face; rock fill material that forms the shell of the dam; and a grout curtain that was constructed in stages within the dam foundation.

Initial estimates of hydraulic conductivity for the dam components were made from laboratory tests, in-situ test data, and previous hydrogeologic assessments of dam seepage. Dam deformation modelling was performed as part of other investigations to provide predictions for the future behaviour of the concrete face. The analyses suggest that the concrete face may experience progressive cracking as the dam crest, tailings and pond elevation rise. The effect of the cracking on the hydraulic conductivity of the concrete face was evaluated as part of model calibration.

Tailings and transport water from the Antamina mine are deposited into the Antamina Tailings Impoundment. This impoundment presently extends nearly 3 km south of the dam face and is approximately 1 km wide. The tailings basin is unlined and is contained by the slopes of the bedrock valley as well as the dam. During the initial filling of the dam, tailings were deposited below the pond surface from the left abutment and from spigots on the dam face. After a beach developed, tailings were deposited sub-aerially from a series of spigots along the dam face and from a discharge point on the southwest valley wall. Hydraulic testing of tailings in the basin indicated that the fines content of the deposited tailings increased significantly on the upstream side of the intersection of the tailings pond with the beach. The testing also indicated that the initial deposition mode (sub-aqueous versus sub-aerial) did not significantly affect the grain-size distribution close to the dam face. Overall, tailings deposited close to the dam face are referred to as “coarse tailings”, whereas tailings deposited further away and generally upstream of the tailings beach are referred to as “total tailings”.

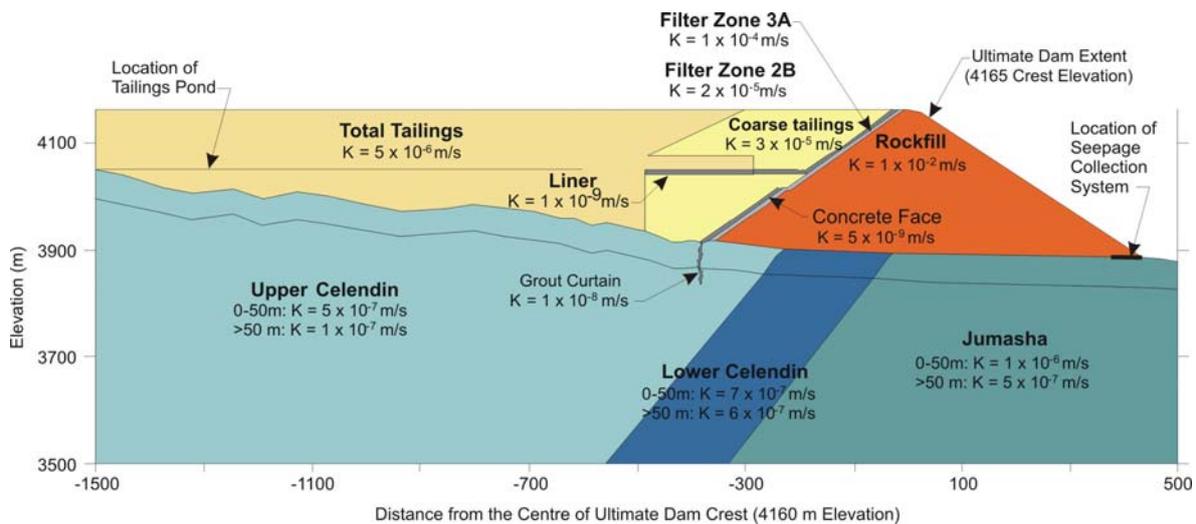


Figure 2. Conceptual Cross-Section through the Center of the Tailings Impoundment and Calibrated Hydraulic Conductivity Values

In addition to the dam, three tunnels have been constructed at the site. The diversion tunnel for the dam is located within the right abutment of the dam. Although plugged, this tunnel is inferred to act as a local groundwater sink that collects some seepage water down-gradient of the plug, which then discharges into the down-gradient shell of the dam. In addition to the diversion tunnel, the two decant tunnels are also located within the right abutment. Groundwater inflows to these tunnels are discharged into a down-gradient creek.

Groundwater Flow Directions

Pre-construction contours of measured hydraulic heads indicate that groundwater flow was directed from sides of the valley towards the valley bottom. In the Upper Celendin, groundwater levels mimicked topography, while in the Lower Celendin and Jumasha formations, the hydraulic heads were often relatively close to or at the valley bottom. This observed difference in hydraulic heads was inferred to be associated with deeper karstic features that may be present in the Lower Celendin and Jumasha units, thus increasing the bulk hydraulic conductivity of these two units. Hydraulic heads in the vicinity of the dam measured in 2007 (current conditions) indicate groundwater flow is presently directed from the tailings pond towards the dam face, with some groundwater flow from the tailings impoundment directed around the right and left abutments. Near the right abutment and near the center of the tailings beach localized lows in the water tables are observed. This could be an indication of potential cracking of the concrete face and/or the presence of higher permeability features in the bedrock.

3. NUMERICAL MODEL

The numerical hydrogeologic model for the Antamina dam was based on the conceptual hydrogeologic model. The finite element mesh used in the model is presented in Figure 3. Horizontally, the model extends from approximately 1500 m up-gradient of the potential ultimate dam crest (4165 m) to 500 m down-gradient of the crest, and from 1100 m to the northwest of the dam centerline to 1000 m to the northeast of the dam centerline. Vertically, the model extends from 3500 m elevation to 4165 m elevation. Relative to the dam footprint, the model extends over 300 m to either side of the dam, and over 350 m below the base of the dam.

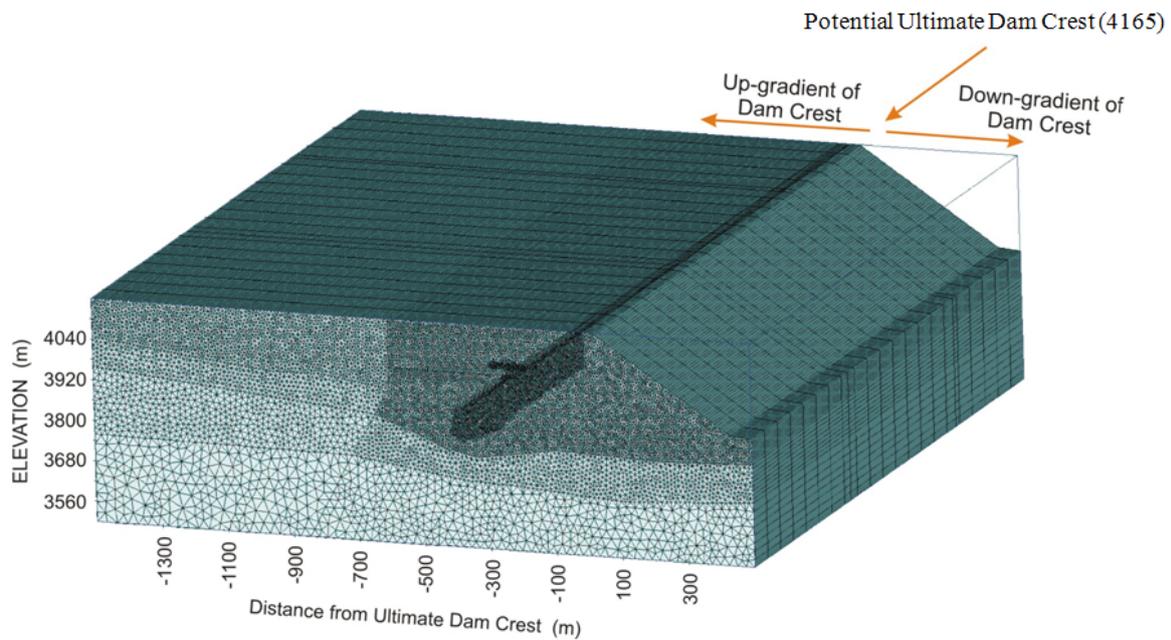


Figure 3. Finite Element Mesh

In order to adequately represent the engineered components of the dam, the model was constructed using 24 vertical sections. The width of each section varied between 30 m and 100 m. Vertically, the size of the finite elements varied from less than 5 m near the dam face up to 40 m near the up-gradient limits of the model. The total number of elements in the finite element mesh is approximately 550,000. This grid is considered sufficient to adequately represent the hydrostratigraphy and the features of the dam.

Three types of boundary conditions (specified-head, specified-flux and no-flow) were used in the model. Specified head boundaries were used to represent the seepage collection system at the toe of the dam. This boundary was constrained by flux, which allowed groundwater to exit the model at these nodes but did not allow groundwater inflow. Specified head boundaries were used to simulate the tailings pond, and the boundary was varied temporally and spatially according to the simulated pond elevation and corresponding position of the tailings pond and beach. Specified head boundaries were also assigned to the northeast and southeast model boundaries to represent regional groundwater inflow from the sides of the valley. All other boundaries of the model were assigned a no-flow (zero flux) boundary condition. This is considered reasonable as the model boundaries are generally parallel to inferred groundwater flow lines, and in the case of the up-gradient boundary, the groundwater flow is likely dominated by seepage water from the tailings pond. The base of the model is considered sufficiently deep, such that groundwater flow from below the base the model (3500 m elevation) is assumed to have negligible influence on hydrogeologic conditions near the base of the tailings dam.

The decant tunnel and the diversion tunnel were represented in the model using one dimensional discrete feature elements. This elements were assumed to have cross-section areas equivalent to that of the tunnels, and were assigned a hydraulic conductivity that was sufficient high to allow virtually unrestricted flow.

4. MODEL CALIBRATION

The hydrogeologic model was calibrated to past dry-season hydrogeologic conditions for six pond elevation stages (Table 1). Dry season flows were used because wet season flows are strongly influenced by infiltration of rainfall into adjacent slopes, and hence do not represent seepage from the tailings dam or abutments. Recharge from precipitation was therefore not simulated in the model.

Table 1. Pond Elevation Stages

Pond Elevation (m)	Approximate Seepage Flow from Tailings Impoundment (Estimated/Measured)	Description
3990	50 L/s	No tailings in impoundment
4013	90 L/s	Pond Below Starter Dam face (4015 m elevation).
4018	170 L/s	Pond Above Starter Dam face.
4039	285 L/s	2005 dry season – before geomembrane liner installed at 4042 m
4047	200 L/s	2006 dry season – after geomembrane liner installed at 4042 m
4054	220 L/s	2007 dry season (current conditions)

For each calibration stage, the assigned hydraulic conductivity zones, discrete feature elements and boundary conditions were adjusted in the model to reflect the status of the grout curtain, the decant tunnels and the tailings pond. The calibration was based on a single transient model simulation that considered sequential increases in pond elevation. Although this simulation was run in transient mode, the simulation time for each calibration stage was sufficiently large to achieve steady-state conditions. The approximation of steady-state conditions is considered reasonable since the bedrock specific storage is likely quite low (i.e., hydraulic heads in the bedrock will respond quite quickly to changes in flow boundary conditions).

The calibration targets for each pond elevation included the measured seepage from the tailings dam, hydraulic head measurements in over 40 piezometers installed in the tailings beach and bedrock abutments, and measured dry season discharge through the diversion tunnel. During calibration the model was run repeatedly and the model parameters were iteratively adjusted until a reasonable agreement between simulated and observed heads and flows was obtained. Figure 4 presents the observed match between measured and predicted flows. This match is not linear as engineering features of the dam (i.e., grouting, liner placement, tailings composition) changed over time as the pond elevation rose. During calibration, the degree of cracking in the concrete face was adjusted to improve the match between measured and model predicted seepage rates. The observed size of the hydraulic sink in the tailings beach area suggested that cracking of the concrete face may have occurred over a 100 m width. The actual extent of cracking and the apertures of the cracks cannot be determined. An iterative process that considered the potential crack apertures and lengths, resulting effective hydraulic conductivity, and the resulting seepage, were used to infer a final effective hydraulic conductivity for the 100 m cracked portion of the face.

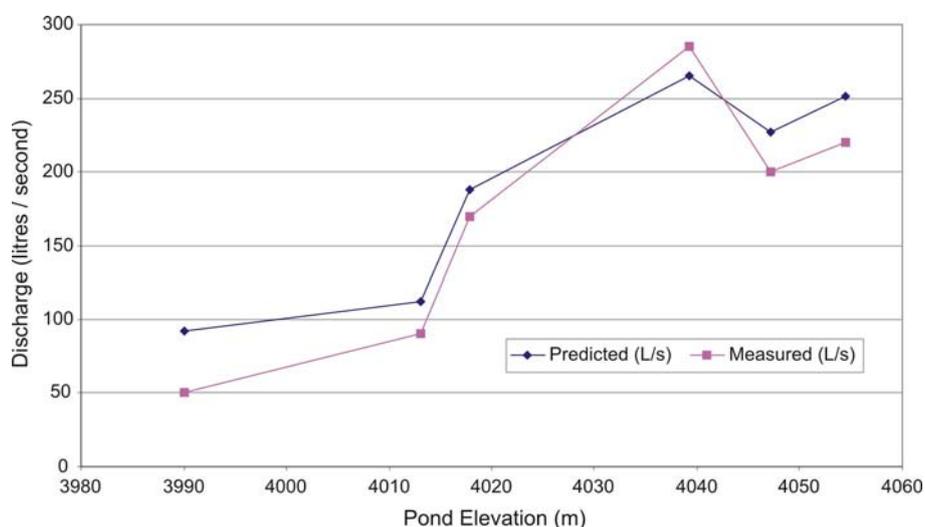


Figure 4. Measured versus Predicted Discharge

5. PREDICTION OF FUTURE HYDROGEOLOGICAL CONDITIONS

The calibrated model was used to provide predictions of future dry-season seepage through the tailings dam during mine operation and following closure. For the predictive scenarios, changes were made to the engineered components of the dam to reflect expected future conditions. These conditions included changes to the beach length during operation and post closure (100 m and 500 m respectively); changes to the extent of the grout curtain and predicted extent of cracking in the concrete face; and continued placement of the geomembrane along the dam face.

For predictive scenarios it was assumed that the geomembrane liner will remain intact during dam operation but will fully degrade immediately at closure (a conservative assumption). The predictive scenarios also considered two potential closure pond elevations (4120 m or 4160 m).

Figure 5 presents a summary of the predicted dry-season seepage during future dam operation and after closure. Overall, the seepage through the dam was predicted to increase in a linear fashion as the elevation of the tailings pond increased. If the dam is raised such that the ultimate pond elevation is 4160 m (crest elevation 4165 m), the dam seepage was predicted to be approximately 650 L/s. Following mine closure and the anticipated degradation of the liner, seepage rates were predicted to increase up to 950 L/s, or by approximately 45% from the end-of-mining seepage. How quickly the degradation of the liner will occur is unknown, although large sections of the liner may remain intact for hundreds of years. Although the impacts of wet-season precipitation were not assessed as part of this work, it can be anticipated based on historical data that discharge rates to the collection system during the wet season could increase from the dry season rates by at least 400 to 500 L/s. The contribution to seepage of wet season inflows would not be expected to increase significantly over the life time of the dam unless the seasonal precipitation also increases.

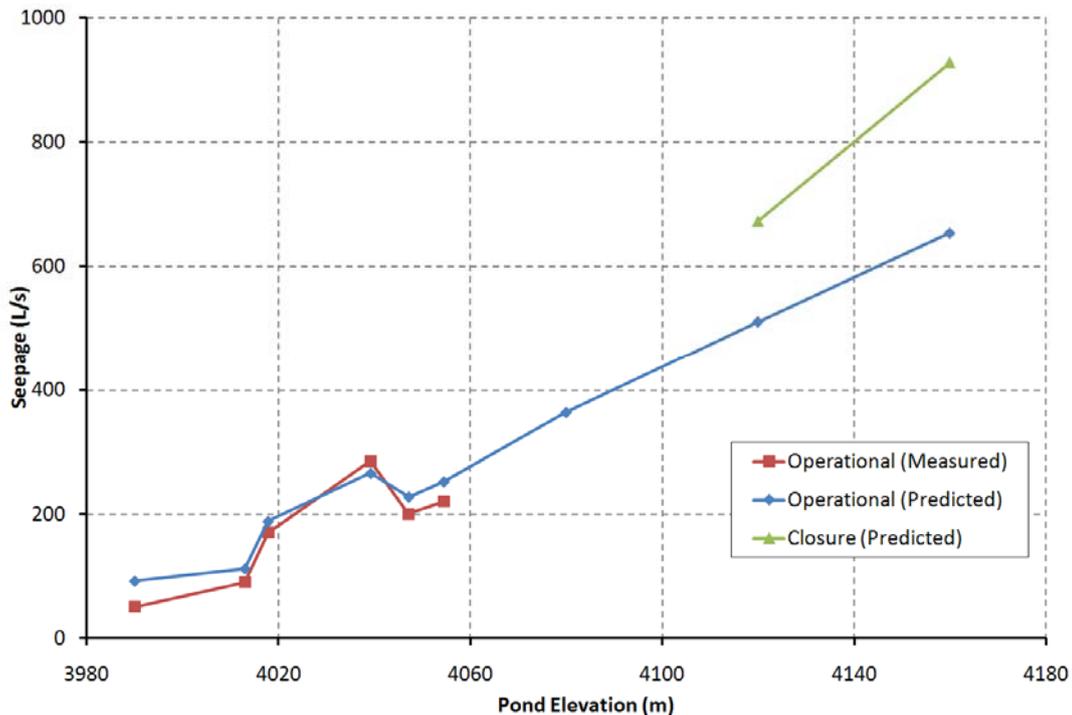


Figure 5. Measured versus Predicted Seepage

6. SENSITIVITY ANALYSIS

The uncertainty in the dam seepage predicted for the future stages of the tailings pond and after closure is controlled by the hydraulic properties assumed for the engineered components of the dam and the tailings and by the hydraulic properties assumed for bedrock. Consequently a sensitivity analysis was conducted where the properties of the engineered components and bedrock were varied from the calibrated values and the change in the predicted seepage was calculated. This analysis identified the components of the dam or bedrock features that have the greatest influence on future seepage, and provided an approximate measure of the uncertainty in the seepage predictions.

The sensitivity simulations were completed for a pond elevation of 4160 m. Properties that were varied in the sensitivity analysis included: the hydraulic conductivity of the tailings deposited in the future (above an elevation of approximately 4070 m); the magnitude of cracking in the concrete face; the length of the tailings beach after closure; and the hydraulic conductivity of the bedrock units.

For the bedrock portion of the sensitivity analysis, three scenarios were considered. In the first scenario, the bedrock hydraulic conductivity of all the units was adjusted up and down by a factor of three from the base case values. In the second scenario only the hydraulic conductivity of Jumasha unit was changed, and in this scenario it was increased by a factor of 10. The Jumasha unit shows some evidence of karst, and it was considered possible that the assigned equivalent hydraulic conductivity in the model was too low. In the third scenario, the hydraulic conductivity of the bedrock was assumed to be anisotropic. The assigned hydraulic conductivity was changed to be 100 times higher in the direction parallel to bedding than perpendicular to bedding. In addition, the principal directions of hydraulic conductivity ellipsoid were rotated to match the orientation of the bedding.

As presented on Figure 6 the seepage during dam operation was predicted to be relatively insensitive to the hydraulic conductivity of the tailings above 4070 m and somewhat sensitive to the hydraulic conductivity of the bedrock and the amount of cracking in the concrete face. If the concrete face was assumed to be fully degraded (i.e., essentially not present) seepage was predicted to increase by approximately 30% from the base case value. This result was considered reasonable as during operation seepage was inferred to be primarily controlled by the hydraulic properties of the tailings already deposited below the geomembrane liner, and the competency of the geomembrane liner, which was assumed to be intact until after closure. The bedrock sensitivity analysis indicated that the predicted seepage during operation was sensitive to the hydraulic conductivity of the bedrock and the potential influence of the bedding surfaces. For these bedrock sensitivity scenarios, predicted seepage was predicted to increase by up to 46% (from 650 L/s to 950 L/s).

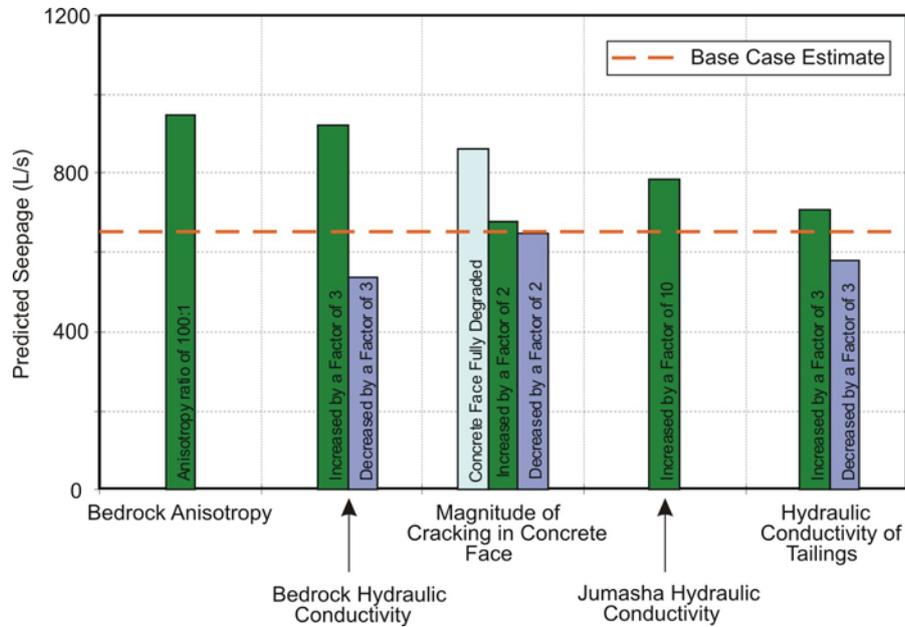


Figure 6. Sensitivity of Predicted Seepage to Model Input Parameters, 4160 m Pond Elevation, Mine Operational

Following closure and the degradation of the liner, the predicted seepage was most sensitive to the engineered components of the tailings dam and less sensitive to the bedrock properties assigned to the model (Figure 7). The two most significant factors affecting seepage are the hydraulic conductivity of the tailings above 4070 m and the length of the tailings beach. If the hydraulic conductivity of the tailings were to increase by a factor of three relative to the current hydraulic conductivity of the tailings, the predicted seepage could increase by approximately 90% from the base case value. Similarly, if the beach length were to be reduced to 300 m at closure, the predicted seepage was predicted to increase by approximately 60% relative to a beach length of 500 m assumed in the base case.

7. CONCLUSIONS

To assess future seepage through the dam and bedrock abutments, a three dimensional hydrogeologic model of the study area was constructed using FEFLOW and calibrated to measured dam seepage, tunnel inflow, and hydraulic heads measured in the dam abutments and in the tailings. Future dam seepage was then predicted for the operation and post closure periods.

Overall, the seepage through the dam was predicted to increase in a linear fashion as the elevation of the tailings pond increased. Assuming a maximum pond elevation of 4160 m, seepage could increase up to 650 L/s during operation, and up to 950 L/s following mine closure and the degradation of the liner. Although the impacts of wet-season precipitation were not assessed as part of this work, it can be anticipated based on historical data that discharge rates to the collection system during the wet season could increase from the dry season rates by at least 400 to 500 L/s.

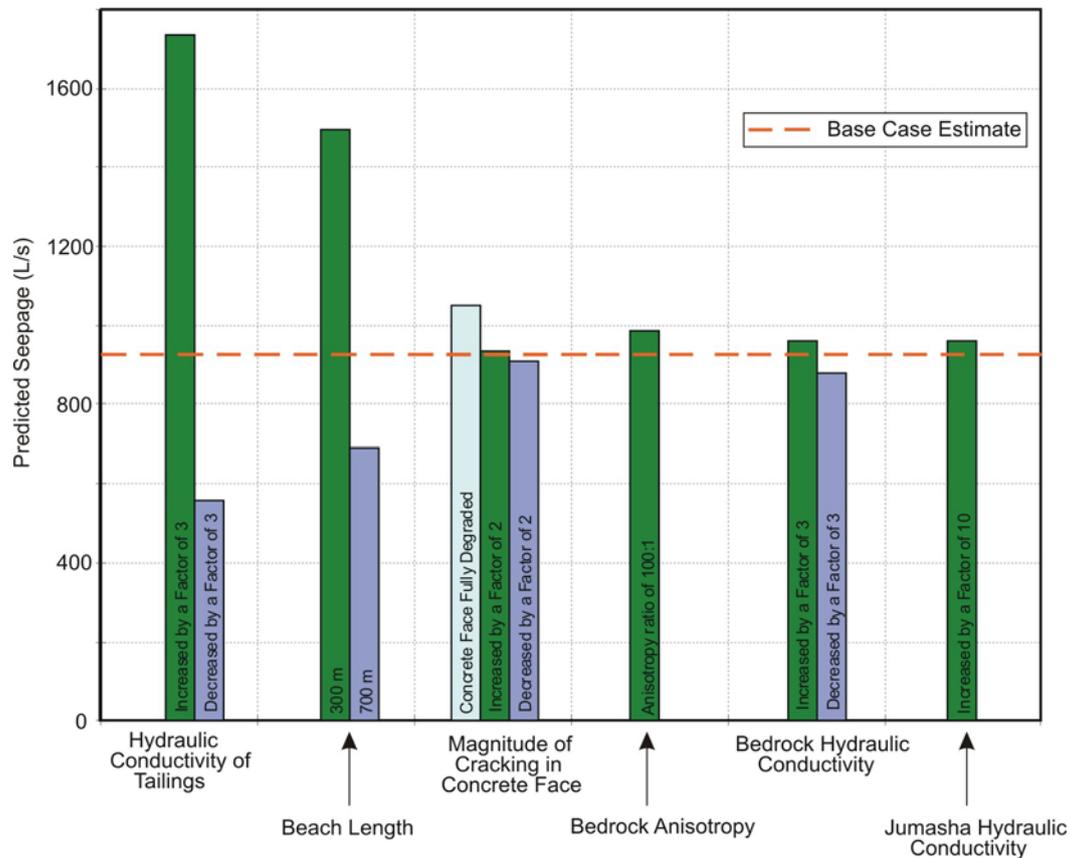


Figure 7. Sensitivity of Predicted Seepage to Model Input Parameters, 4160 m Pond Elevation, Post Closure

During mine operation, predicted seepage was found to be most sensitive to the hydraulic conductivity of the bedrock and extent of cracking in the concrete face. Following mine closure and the degradation of the liner, predicted seepage was found to be most sensitive to the engineered components of the tailings impoundment (beach length and the hydraulic conductivity of the tailings) and less sensitive to the bedrock properties.

8. REFERENCING

Diersch, H.G. (2007) *FEFLOW v. 5.3 Finite Element Subsurface Flow and Transport Simulation System*, WASY Institute for Water Resources Planning and System Research Ltd., Berlin, Germany.