Groundwater Issues in the Design, Operation, and Closure of Tailings, Waste Rock, and Heap Leach Facilities

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ABSTRACT: This paper deals with the many ways in which mine waste disposal facilities, including tailings, waste rock, and heap leach facilities may interact with their adjacent groundwater system. The paper first categorizes and discusses ways in which groundwater conditions at the mine site may affect the design, operation, and closure of such mine waste disposal facilities. The paper then proceeds to categorize and discuss ways in which a mine waste disposal facility may conversely impact groundwater systems. The paper lists and describes engineered systems that may be needed to control the interaction of mine waste disposal facility and groundwater, including: liners, drains, cut-off walls, and dewatering wells. The paper provides guidance on theoretical and analytical methods that may be used to model and hence quantify interaction between waste facilities and groundwater and to evaluate and assess potential impact by mine waste disposal facilities on groundwater.

1 INTRODUCTION

1.1 *Interaction of Mine Waste Disposal Facilities and Groundwater*

Hydrogeological conditions at the site of a tailings facility, a waste rock dump, or a heap leach pad significantly affect the design, operation, and closure of such facilities. Seepage of process water and constituents from a facility may affect the state of the groundwater system. Conversely, local groundwater may surface as springs or rise up into this facility and thereby affecting the overall performance of the facility.

This paper examines the many ways in which mine waste disposal facilities may interact with a groundwater system. The paper illustrates some specific situations that arise and suggests ways to address issues related to the interaction of mine waste disposal facilities with groundwater. This is done by drawing on practical examples—actual case histories are not quoted but the examples used are based on practice and situations of which the authors are personally aware.

1.2 *Facility and Groundwater Modeling*

At the behest of the British Columbia Ministry of the Environment, Water Protection & Sustainability Branch, the authors along with colleagues in Robertson GeoConsultants and SRK prepared guidelines for groundwater modeling to assess impacts of proposed natural resources development activities in British Columbia—see BC MoE Groundwater Modeling Guidelines at this link: www.rgc.ca/moe/. This paper draws on the guidelines in order to illustrate analytical approaches to modeling seepage through and from mine waste disposal facilities to the site groundwater.

2 GROUNDWATER AS A FACTOR IN FACILITY DESIGN, OPERATION AND CLOSURE

2.1 *Site Selection and Design*

Ideally, selection of a new site for a mine waste disposal facility should identify a site with little or virtually no groundwater present across the uppermost portion of the subsurface. There are, however, few mine sites where the conditions are similar to those found at the Utah Monticello uranium mill tailings facility. There the foundation materials are characterized by deep, thick layers of Mancos Shale, a geologic formation which was deposited in offshore and marine environments and which acts now as a low permeability aquitard with little groundwater of poor quality.

In the far north of Canada and Alaska, the ground may be permanently frozen. The authors know of mine tailings facilities in such environments where groundwater is not an issue: it is frozen, the tailings freeze, and there is thus little likelihood of seepage.

At the other end of the scale, in desert areas such as occur in Nevada, northern Chile, and large parts of Australia, there is little if any groundwater at the selected site. In fact, the tailings facility is likely to be the largest single potential contributor to aquifers. In such circumstances, issues of lining, tailings permeability, and downstream cut-off facilities quickly arise and need to be analyzed.

When the local climate of a site is characterized by moderate to high rainfall, groundwater recharge may be significant and thus result in the occurrence of a shallow water-table. In this case, the potential for seepage of contaminants into downstream aquifers should be assessed early enough during the design stage of the mine waste facility. It is recommended that extensive site characterization work be completed to develop a good understanding of the local hydrogeologic setting under baseline conditions. Typically, such work may include:

- Geological and geophysical surveys
- Geotechnical investigations
- Hydrologic analyses
- Hydrogeologic investigations

These studies should define the layout of local geologic formations and establish their geotechnical and hydrogeologic properties. The main focus should be to obtain representative estimates of the hydraulic conductivity (K) of these formations in order to evaluate their transimissivity and to in turn identify preferential flow paths for groundwater.

More and more mines are considering tailings thickening or filter pressing as ways to reduce overall water consumption and to produce low permeability wastes of low moisture content that are unlikely to result in significant seepage to groundwater. For example, the proposed Rosemont Copper mine south of Tucson, Arizona, has selected filter pressed tailings for these reasons.

2.2 *Operation and Routine Monitoring*

Assume the selected tailings facility site is in an arid area and is underlain by deep, permeable sediments. Assume there is groundwater deep in the sediments, and local concerns give rise to the need to limit seepage to the groundwater lest it be impacted.

Assume the embankment dam needs to be lined with a geomembrane. This is required to limit seepage through the embankment, which in addition will include seepage collection drains. The question quickly arises: how far up the reservoir area (i.e., that part of the facility where the tailings will be deposited) need the liner to be extended.

Consider: at the start of operation, water emanating from the deposited tailings will pond against the embankment. If there is no liner, much if not all the pond water may seep into the foundations soils, to be lost, or to induce water pressures potentially detrimental to embankment stability.

As the tailings are deposited into the reservoir, basal seepage of water from the newly deposited tailings to the foundation soils will occur. The rate of such seepage, which we may term exfiltration, is a function of the permeability of the tailings and the foundation soils, the moisture content (hence water entry pressure) of the foundation sols, and the rate of consolidation of the tailings as subsequent lifts are placed. And as consolidation of the lower part of the tailings lift occurs, there is most likely a significant reduction of permeability of the lower layer of tailings and hence reduced seepage to foundation soils.

To analyze this, it is necessary to characterize the tailings and foundation soils, to undertake deposition modeling, and to quantify the consolidation of the tailings as a function of rate of deposition and rate of rise. Then impose the seepage quantities thus estimated on the groundwater to ascertain impact, if any.

To model these processes, it is in turn necessary for the modeler to be able to rely upon a representative set of monitoring data. Hence a groundwater monitoring network should be implemented prior to and throughout the operation of a mine waste disposal facility, with the objective to monitor and generate historical records of the parameters of interests; such parameters may include:

- Depths (and fluctuations) of the water-table and deeper groundwater levels
- Groundwater quality for selected contaminants of concern (COC)
- Surface-water flows and water quality
- Phreatic levels in embankment dams
- Seepage flow rates and water quality in underdrains

These parameters should be monitored using dedicated monitoring devices, including monitoring wells, piezometers and weirs. Once in place, the monitoring network should be surveyed as specified by a groundwater monitoring plan. Data should be collected and evaluated by personnel trained to do so. The frequency of surveying intervals should be defined based on the nature of the groundwater regime and waste disposal operations. Highly seasonal climates may induce significant transient changes in the groundwater regime that warrant monthly monitoring surveys. On the other hand, dry climates may produce relatively steady conditions and thus only necessitate semi-annual surveys. See Section 4.5 for details on the use of the observational method.

2.3 *Closure*

At closure a cover will probably be placed over the tailings facility, waste rock, or heap leach pad. The cover should be such that it acts, in the long term, as the primary impedance to infiltration to the wastes and hence exfiltration from the facility. A well-close mine waste disposal facility should not have to rely on a liner, if there is one, to limit potential groundwater impact. For in the goodness of time, liners will decay and fail to control exfiltration.

If the cover functions properly, any water entrained in the wastes will, with time, seep out. Transient seepage analyses are required to quantify the period over which such drawdown of any water table in the waste will occur. The challenge is to establish by predictive seepage modeling that in the long term there will be no continuing impact on groundwater. Note that as a preliminary basis, engineering estimates of seepage from tailings impoundments for example can be obtained using relatively simple analytical solutions such as the approach presented by McWhorter and Nelson (1978).

It may be necessary to invoke geochemical processes including attenuation to establish long-term groundwater protection. If this cannot be done, it may be necessary to install cut-off walls, seepage recover systems, or grout curtains to limit long-term groundwater impacts.

3 FACILITY IMPACTS ON GROUNDWATER

In principle, seepage from a mine waste disposal facility can originate from different sources. For the case of a tailings impoundment, seepage may be sourced from one or many of the following components:

- The embankment dam
- Slimes deposits (tailings pore water)
- The decant pond

The relative impacts from either one of these sources will ultimately depend on their connection with the foundation soils or rocks and their permeability. Provided high permeability materials are identified, the designer may have to recommend the installation of a low-K liner. Similar measures may be endorsed for waste rock dumps and heap leach pads.

It follows that a mine waste disposal facility may have one or more of the following impacts on the local and regional groundwater systems:

- Raise the elevation of the water table as a result of increase input of water to the subsurface soils and rock.
- Lower the elevation of the water table as a result of reduced inflow to the foundation soils and rocks—this may occur where a liner is used or the tailings are of lower permeability than the permeability of the upper surface of the foundation sols before deposition begins.
- Introduce constituents (contaminants) into the groundwater thereby causing changes in groundwater quality.
- Change the flow rate at springs or surface seeps where groundwater passing beneath the waste disposal facility is affected by increased flow, reduced flow, or the introduction of contaminants.

For complex settings, numerical modeling of seepage may be necessary to quantify these impacts. This topic is now addressed in the following section.

4 SEEPAGE MODELING

4.1 *Modeling Objectives*

The first step in any seepage and/or groundwater modeling is the setting of specific modeling objectives. In the case of seepage from a mine waste disposal facility into a local groundwater system, the following are some typical modeling objectives:

- Predict the future (transient) volumetric flow of seepage from the tailings facility during operation.
- Predict the future contaminant transport from the waste rock dump to a specified valued ecosystem during operation and post-closure.
- Predict the reduction on impacted groundwater in response to alternative seepage mitigation strategies (e.g., drains, interceptor wells, etc).

4.2 *Data Review and Compilation*

Before modeling, collect and collate data about the site and the mine waste disposal facility. This includes information about the following:

- Local and regional geology, lithology, bedrock structures (including faults and dikes)
- Spatial distributions and temporal variations in groundwater flow levels, flow directions, and flow rates.
- Spatial distribution of hydraulic properties such as hydraulic conductivity, transmissivity, specific yield and specific storage. These properties are typically obtained by means of field and/or laboratory hydraulic testing.
- The geotechnical characteristics of the tailings, waste rocks, materials of the heap leach pad, and of foundation soils and rock.
- Surface water hydrology and climate as it may influence the waste facility hydraulic performance and the groundwater flow patterns.

4.3 *Conceptual Model*

There are many varied definitions of seepage and groundwater conceptual models. Regardless of the definition, a conceptual model must be formulated before proceeding to numerical modeling. This is one workable definition of a conceptual model for groundwater evaluations:

> A conceptual model is a simplified representation of the essential features of the physical hydrogeological systems and its hydraulic behavior, to an adequate degree of detail to enable the

questions at hand to be answered.

The conceptual model should be as simple as possible but no simpler than the complexity of the real situation demands. Include key components of the mine waste disposal facility including covers, liners, and perimeter containment embankments. Include key features of the geology as it affects the groundwater flow, including hydrostratigraphic units (i.e. aquifers, aquitards and aquicludes), faults, dikes, and the many layers of soil and rock of variable hydraulic conductivity that make up the groundwater system of interest. Compute a groundwater balance, which includes the natural contribution and artificial contribution of water/seepage to the system. If relevant, evaluate the degree of groundwater and surface-water interactions as these may result in additional groundwater recharge and/or groundwater discharge. A conceptualization of contaminant transport may also be included as part of the conceptual model. Potential and likely sources of contamination should be specified; the water quality of the resulting seepage plume should be characterized and its spatial extent delineated.

From a mine project standpoint, there are two essentially different conceptual models that need be formulated for projects involving modeling of seepage from a mine waste disposal facility. These are:

- Baseline or preconstruction conditions, i.e., no mine waste disposal facility yet in place.
- Operating phase conceptual model, i.e., the mine waste disposal facility is in place and being operated.

The second is generally more complex than the first. In some situations it may be better to work with two distinct, uncoupled conceptual models and integrate them only as key interactions are likely to occur in practice. For example, seepage from the tailings may be estimated by one model; the seepage flux may be entered as a boundary condition into a second model representing only the groundwater flow system.

The conceptual model should also indicate whether the groundwater regime can be approximated using the assumption of a steady-state or if the need for a transient model is required. Note also that depending on the modeling objectives and data available for calibration, the model may include the waste disposal facility implicitly, or rather as a model boundary condition explicitly.

4.4 *Mathematical Modeling*

There are few closed form equations that may be solved to mathematically model seepage situations as they involve mine waste disposal facilities and their interaction with groundwater. Most projects will demand use of one or more of the many computer codes commercially available. Regardless of which is chosen for a specific project, first try to calibrate the numerical model against conditions as observed and measured in the field. Calibration methods are generally grouped into manual (i.e. “trial and error”) methods and automated method (such as the parameter estimation code PEST).

In the context of mine waste disposal facilities, calibration approaches will differ depending on whether the project involves the design of a new facility, remedial works at an existing facility, or the design of closure works. For a new facility, the best that can be done is to calibrate for existing, pre-mining conditions. If the facility is already in operations and the project involves determination and design of expansion or remedial works, calibration of existing conditions may include the waste facility and seepage therefrom. If the project involves closure of a mine waste disposal facility, there should be historic data that may be used to both calibrate and verify the seepage models.

Once a calibrated numerical model is in place, proceed to predictive modeling. This involves running the model to simulate future performance of the mine waste disposal facility and its interaction with groundwater. Predictive models cannot be calibrated or even checked in the strictest sense. Accordingly it is prudent to model a series of possible cases. For example, one may run simulations for the most likely future performance (expected case), for feasible upper bound conditions, and even for extreme worsts case scenarios. Eventually, the historic record of monitoring data of a mine project should be used as model verification targets, i.e. field observations should be tested against the predictions established by the model. In the case that significant discrepancy arises, the numerical model should be recalibrated in order to simulate the observed groundwater system's response over time.

4.5 *Use of the Observational Method*

The Observational Method as enunciated by Ralph Peck leads itself to use in the context of monitoring and reacting to the performance of mine waste disposal facilities and their interaction with groundwater. This is how Peck formulated the method:

- Exploration sufficient to establish at least the general nature, pattern and properties of the deposits, but not necessarily in detail.
- Assessment of the most probable conditions and the most unfavorable conceivable deviations from these conditions. In this assessment geology often plays a major role.
- Establishment of the design based on a working hypothesis of behavior anticipated under the most favorable conditions.
- Selection of quantities to be observed as construction proceeds and calculation of their anticipated values on the basis of the working hypothesis
- Calculation of values of the same quantities under the most unfavorable conditions compatible with the available data concerning the subsurface conditions.
- Selection in advance of a course of action or modification of design for every foreseeable significant deviation of the observational findings from those predicted on the basis of the working hypothesis.
- Measurement of quantities to be observed and evaluation of actual conditions.
- Modification of design to suit actual conditions.

This is more or less what can be considered current practice in groundwater monitoring in the context of mining and its waste facilities. Yet it is seldom done formally. With the power of modern seepage modeling codes it can be done readily and formally and it is thus recommended that this be done. The outcome may be documented in the facility's *Monitoring and Operating Plan.*

4.6 *Model Documentation*

Typically, the outcome of a groundwater modeling study is a report summarizing the main study findings and recommendations. As numerical modeling is a staged process, the report should clearly document in a concise and transparent manner the development of the model from the conceptual stage to the final, calibrated model stage. A report should thus describe and justify the following information:

- Numerical code selection
- Model domain & boundaries
- Sources & sinks
- Calibration methods & sensitivity analyses
- Model limitations
- Key findings

5 SOME SPECIFIC SITUATIONS

5.1 *Section Overview*

The following are some of the many specifics of mine tailings and water rock interactions with groundwater. For each situation, the general outline of field conditions is shown in a figure. Associated text follows.

5.2 *Basic Components of a Tailings Groundwater Model*

Figure 1 show the most basic components or aspects of a tailings impoundment and a tailings facility. The configuration of the components varies infinitely from site to site, but most include the following:

- Bedrock of low permeability – or maybe higher permeability if it is fractured, faulted, or otherwise disturbed.
- Colluvial and/or alluvial soils of higher permeability.
- A groundwater table most often located at some depth in the more permeable materials.
- The tailings facility itself --- note that the facility generally increases with size over time as the mine operates and more tailings are deposited.
- A river, creek, or waterway to which groundwater flows to emerge as bank seepage, spring, or slow baseflow to the water body.

5.3 *Open Pit*

Figure 2 shows that the situation may be more complex than as depicted in Figure 1. At many mines there is an open pit, which functions in a manner that drastically alters natural groundwater flow conditions. Most often, as the pit increases is size and depth with ongoing mining, the groundwater table is lowered by seepage into the pit or through extraction wells installed to lower the water table and hence reduce the impact of pore pressures on the stability of the pit walls.

Often the waste rock dump and the tailings facility are close to the open pit. As shown in this figure, the waste rock dump is upgradient of the pit. It is probably more cost effective to place the waste rock dump downgradient of the pit. Regardless, as the dump grows there will be infiltrations into the dumps, seepage though the dump, and ultimately exfiltration from the dump. Seepage from the dump may occur as infiltration into the foundation soils and rock or may emerge as springs, seeps, or wet spots at the toe of the dump.

As in Figure 1, the tailings facility may also be a source of increase (or decreased) seepage to groundwater.

Keep in mind that the situation shown in Figure 2 is but a snapshot of one instance in time of the potential interaction of mine waste disposal facilities and their adjacent groundwater system. The pit is ever getting broader and deeper; the waste rock dumps are ever getting larger and more extensive. The tailings facility is always expanding out and up.

For this reason, mine-related groundwater models should be developed in a manner which allows them to be adjusted in order to reflect the incessant change of mining conditions and mine and groundwater interaction. In some instances, the model may have to be updated and recalibrated using new model parameters and additional monitoring data.

5.4 *Tailings Seepage Control Facilities*

Figure 3 and 4 show some of the many components that may be included in a tailings facility to control, limit, or eliminate seepage from a tailings impoundment to the underlying groundwater system. Such interception systems may be required to impede the passage of contaminants from the tailings impoundment to the groundwater system, downgradient water bodies, and ultimately human, animal, and plant receptors. Alternatively, these systems may be also needed to limit water losses in arid climates.

Typically, seepage interception systems (SIS) consist of a barrier, either physical or hydraulic, which impedes the flow of groundwater further downstream. Physical barriers include cut-off-walls, sheet piles and grout curtains. Hydraulic barriers consist of seepage interceptor trenches and/or extraction wells. Interceptor trenches are often considered cost-effective measures for shallow applications, i.e. when the water-table lies close to the ground surface. On the other hand, extraction wells represent the most widely used option for groundwater containment, especially when the depth of the contaminated plume is beyond the constructability of a trench.

Where contamination has been monitored outside the mine’s property boundary, it may be required to provide a solution scheme for the residual contamination downstream of the interception system. One possible mitigation option for shallow plumes is the installation of an infiltration trench downstream of the interception system. In this case, contaminated groundwater is first intercepted to prevent future seepage from the mine waste disposal facility, and clean water is infiltrated downstream in order to accelerate the dilution of the residual plume via artificial means.

Many argue that with time the lower layer of the tailings consolidates and becomes a layer of low permeability, thus effectively “lining” the facility. If the tailings are clayey, and they consolidate reasonably fast (a bit of a contradiction to be sure) it is feasible a liner-type situation may come to be. Only detailed tailings and groundwater seepage analysis (modeling) will enable you to explore and prove what is likely to happen.

5.5 *Tailings Causing Rise of Groundwater Table*

Figure 5 shows how a tailings facility may act to increase the elevation of groundwater at the site of the tailings facility. Say, as shown in the first frame, the groundwater seeps naturally to the base of the valley where the tailings are to be placed. With time as the elevation of the tailings increases in the valley, groundwater can no longer seep at pre-construction rates into the valley, and instead the water-table is forced to rise along with tailings.

This is generally considered a positive happening, as the surrounding groundwater seeps into the tailings and thereby substantially reduces the potential for contaminant migration from the tailings facility to the environment.

But beware of the three-dimensional issues. At the embankment dam, seepage may still be directed outwards from the tailings facility. Or, worse, inward seepage from the foundation to the embankment may induce piping and foundation failure. That is what caused the Teton Dam to fail and kill many.

5.6 *Waste Rock Dump Acid Drainage*

Figure 6 shows a condition that lead to great expense. The upper clayey soils at the site of the proposed waste rock dump were stripped. This was done as the soils were of too low a strength to provide for the stability of the proposed waste rock front slopes. Stripping the upper layer of lower permeability soils exposed higher permeability fractured bedrock.

Then the waste rock was dumped. The dump grew bigger and bigger.

As the waste rock was very permeable, rain that fell on the dump infiltrated, seeped on through, and flowed into the bedrock. This additional infiltration to the bedrock caused the groundwater table to rise. It rose so high that it entered and hence seeped through the waste rock.

The waste rock is acid generating, and now there is an expensive seepage capture and treatment system in place. If engineers and groundwater hydrologists had been consulted during the mine planning phase, they may have been able to construct basal drains or even avoid stripping away the clay.

5.7 *Closure*

Finally all mines close. A cover is placed on the mine waste disposal units. As shown in Figure 7, the cover should be the only component relied on to limit excess seepage form the waste disposal unit. Liners will not last or at the worst they will simply focus seepage from the waste disposal unit to the toe where it will probably have to be collected for treatment in perpetuity. Note that compliance groundwater monitoring may also be required to ensure that potential future impacts may be evaluated. Ideally, the long-term performance of the groundwater interception systems should be assessed and further evaluated if required using the groundwater model developed during the operational stage of the mine waste disposal facility.

5.8 *References*

McWhorter, D.B. and Nelson, J.D. 1978. Drainage of earthen lined tailings impoundments. *Uranium Mill Tailings Management: Proceedings of a Symposium, Fort Collins, CO. Colorado State University, November 20-21, 1978. Volume 1.* 31-50.

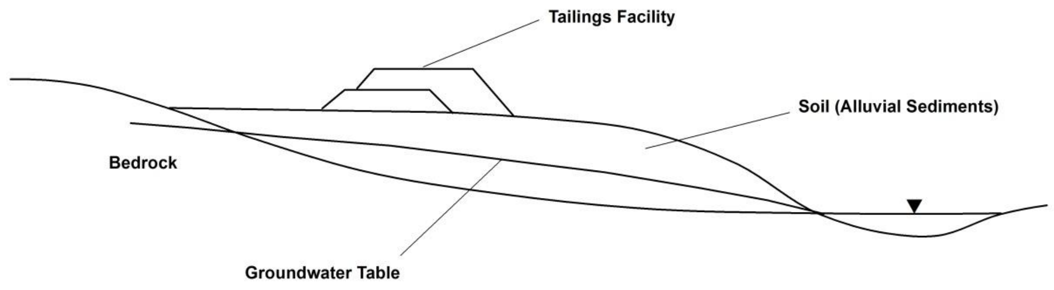

Figure 1
The Basic Components of Tailings Facility and Groundwater Interaction

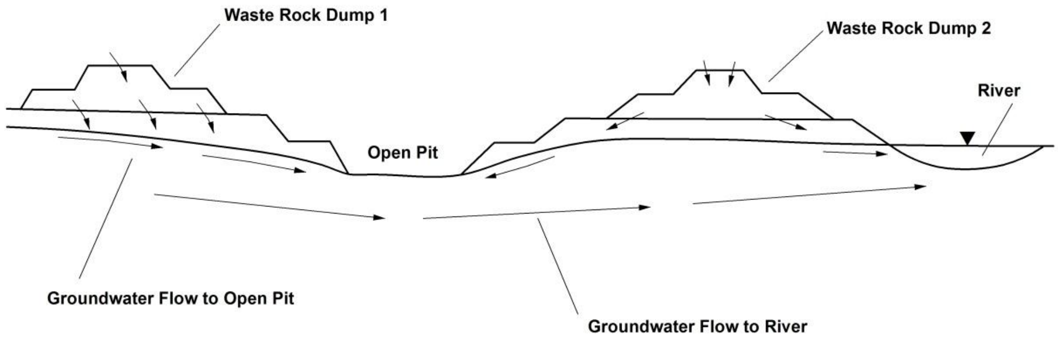

Figure 2
Conceptual Model of Groundwater Flow Conditions Associated with an Open Pit Surrounded by Waste Rock Dumps

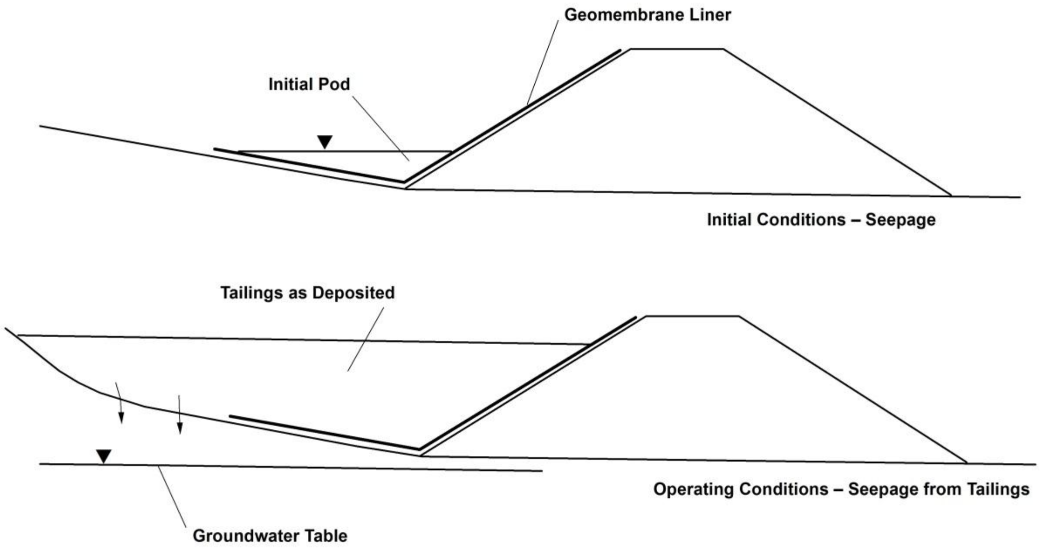

Figure 3
Lined Embankment Dam for Tailings Facility

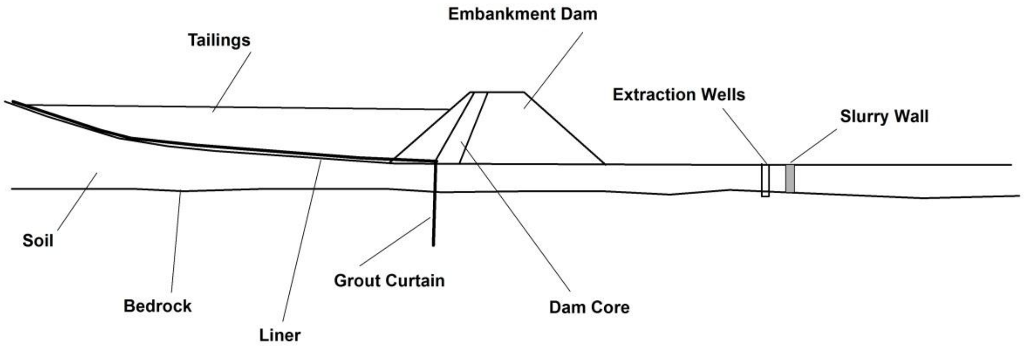

Figure 4
Components of a Tailings Facility
for Seepage Control

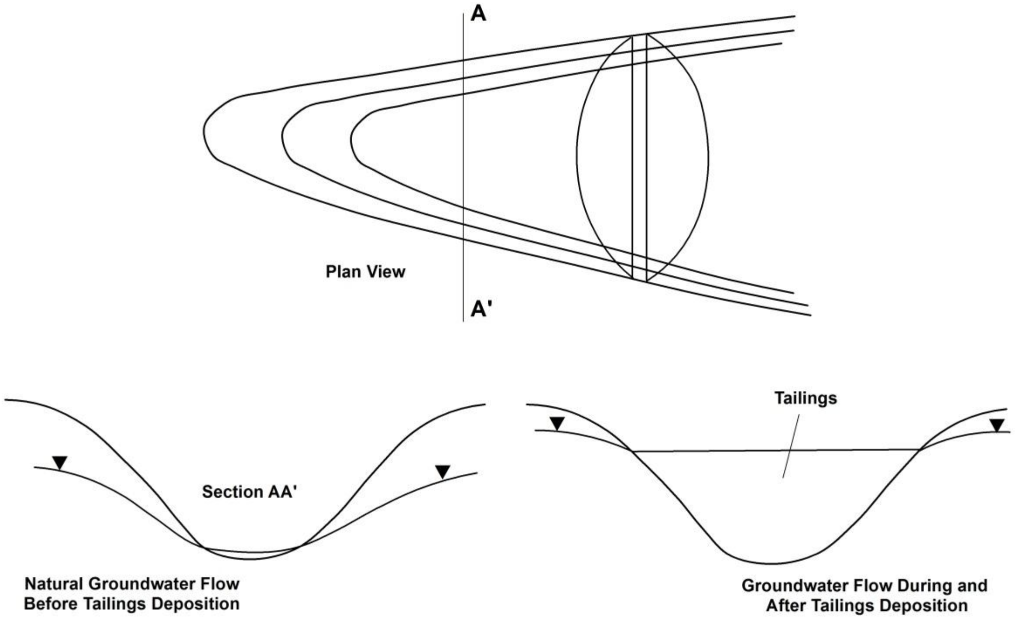

Figure 5
The Groundwater Table Rises
as the Tailings Fill the Valley

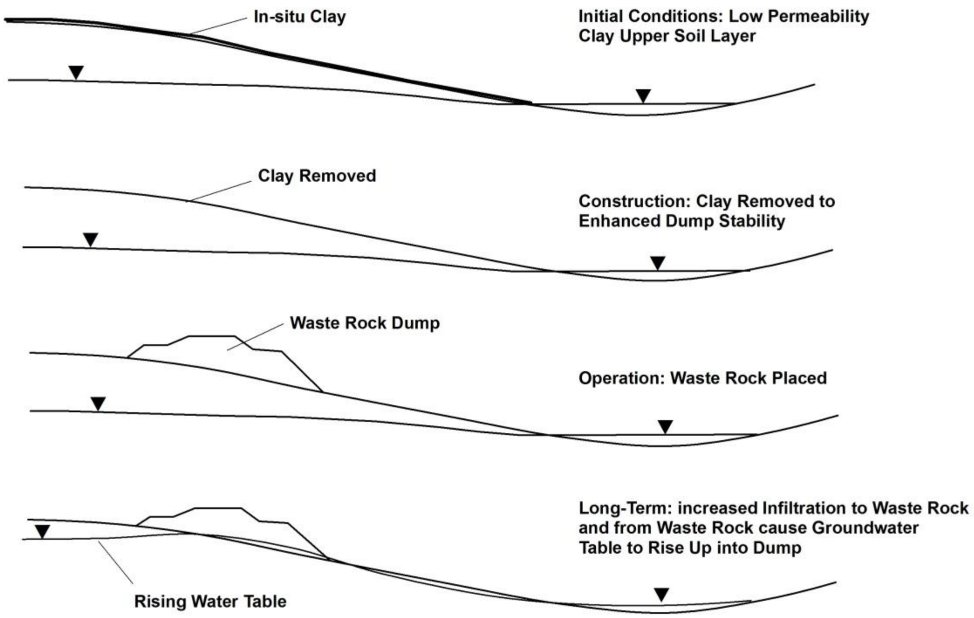

Figure 6
Groundwater Table Rise After
the Removal of Low-Permeability Soils

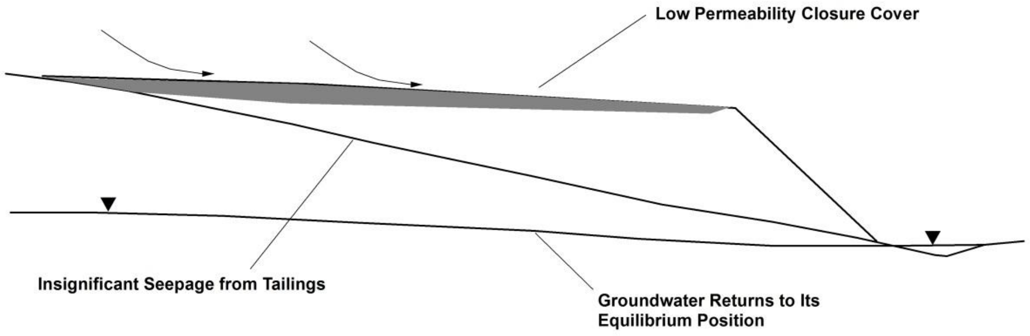

Figure 7
Closure Conditions for Long-Term Modeling