ASSESSING THE HYDRAULIC PERFORMANCE OF TAILINGS MANAGEMENT FACILITIES

H. Garrick, G. Digges La Touche, B. Plimmer and D. Hybert

*Golder Associates (UK) Ltd., Attenborough House, Browns Lane Business Park,
Stanton-on-the-Wolds, Nottinghamshire, NG12 5BL.*

Abstract

Predictions of operational and post-closure leakage rates from tailings management facilities (TMFs) are required from the early stages of design development, both for key aspects of the design (embankment stability, liner and drainage designs) and in order to assess the potential groundwater and surface water impacts of the facility. It is imperative that the approach to facility performance simulation for these assessments is selected with consideration of the modelling objectives, the site setting and the state of knowledge regarding the site. The completion of leakage assessments at an early stage of the project, with limited available data and considerable uncertainty, has a tendency to lead assessors to select a simplified 2-dimensional (2-D) steady state modelling approach. Whilst this approach is appropriate for many TMF design problems a simplification may neglect significant processes. Therefore in some scenarios the use of a 3-D modelling code (e.g. MODFLOW-SURFACT™ or FEFLOW), or a transient modelling approach may be more appropriate. The objective of this paper is to present a discussion of the advantages and disadvantages of typical 2-D and 3-D modelling approaches, illustrated with selected case studies to demonstrate how variations in the approach to assessment can reduce uncertainty in TMF design.

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e-mail: HGarrick@golder.com, GDiggesLaTouche@golder.com

Introduction

All mining activities will result in the generation of wastes, including waste rock (excavated rock which is not ore) and tailings (the residue of the ore refinement or extraction process). The design, operation and closure of a tailings management facility (TMF) is a key part of most mine developments, and effective environmental management of tailings disposal during the mine life and following closure is a significant factor in managing long term environmental impacts of a mine. It is necessary to understand the hydraulic performance of the TMF at the design stage to develop and optimise embankment, liner and drainage designs and to predict environmental impacts. In this paper, 'hydraulic performance' encompasses the movement and ultimate fate of water trapped during deposition or infiltration into the tailings (i.e. below the tailings surface) and associated problems including the following:

- Leakage rates through the base of the facility to underlying groundwater and timescales for movement in groundwater away from the TMF;
- Leakage rates through the bounding embankment or dyke;
- Flow velocities through the bounding embankment or dyke;
- The position of the phreatic surface within the TMF and bounding embankments;
- The quantity of water originating in the TMF, which will discharge to downstream surface water, and the timescale over which discharge occurs;
- Pore water pressures within the TMF and in the bounding embankments; and
- Discharge to drains beneath the facility or at the embankment toe.

Problems regarding hydraulic performance similar to those described above are relevant to other impoundment facilities, including silt lagoons associated with quarrying operations, anaerobic digestion lagoons and water storages, where it may be necessary to estimate rates of leakage from a lagoon, or rates of water recirculation from a lagoon to an adjacent void or discharge.

This paper does not discuss TMF surface water balances, which are typically used to understand requirements to control surface water within the TMF and to establish the volume of water available for reuse.

Tailings characteristics

Tailings comprise milled or ground ore rock reduced to silt-sized angular particles, which may include the residues of chemicals added during mineral extraction and clay minerals where these are present in the original ore. Tailings are conventionally disposed of to a TMF as a slurry comprising 20% to 40% solids by mass (European Commission, 2009), the water component of which is subsequently recovered for reuse in the mine or disposal, following settlement of the tailings. A conventional TMF can therefore be regarded as a slurry impoundment; a surface containment facility where the tailings are stored and allowed to drain and consolidate. Tailings disposal constitutes a permanent disposal of waste to land, which may be re-profiled and capped following operation to a final end state that will remain a feature of the post-mining landscape.

With regard to the physical features and hydraulic behaviour discussed in this paper, silt lagoons associated with gravel washing operations represent smaller, but physically similar, disposal facilities, with the distinction that the silt contained in such lagoons or impoundments is natural (containing clay minerals and naturally rounded grains) and generally chemically inert. Although silt lagoons are typically situated below ground, their position adjacent to quarry voids commonly results in an embankment-type problem, similar to the dammed impoundments described here. Where impoundments or lagoons are situated above the water table, construction above or below ground level has little influence on the leakage and groundwater flow regime surrounding the facility excepting that leakage through perimeter bunds may be more readily intercepted, reducing loss to ground.

Types of TMF

Conventional TMF surface impoundments can be categorised into three primary types: ring dyke, cross-valley and side of hill construction (Vick, 1990), illustrated in Figure 1. Slurry tailings can also be disposed of at surface in the mine pit following excavation. The geometry selected for the facility is dependent on the landform of the disposal site and other design factors including the geology and hydrogeology of the site. Tailings are deposited from single discharge points, spigots positioned around the TMF perimeter, or cyclones situated at the dam crest (United States Environmental Protection Agency, 1994). Free water within the TMF is controlled through abstraction from a decant pond, the location and depth of which is considered in deposition modelling during the TMF design. From a hydraulic perspective, TMFs may be operated either as sub-aerial facilities, where tailings are allowed to dry and oxidise in the open air, or as sub-aqueous facilities, where the tailings are deposited into water to prevent direct contact with air. Sub-aqueous facilities are utilised where it is necessary to reduce oxidation of the tailings and control acid generation, such as for high sulphide tailings (e.g. at the Lisheen mine in Ireland (European Commission, 2009)). The mode of operation of the facility (sub-aqueous/sub-aerial) and position and depth of the decant pond are significant factors in the hydraulic performance of the TMF. The physical and hydraulic properties of the tailings, embankments and underlying ground, and natural groundwater flow conditions are fundamental to developing an understanding of hydraulic performance.

Drivers for hydraulic performance assessment

The drivers for hydraulic performance assessment of TMFs are two-fold: design and engineering optimisation, and environmental impact assessment.

At the design stage, simulation of the phreatic surface and seepage through the embankment is an essential, and therefore routine, element of TMF design required to assess embankment stability and the risk of internal erosion in embankments. This is a mathematically complex problem discussed in many texts (summarised in Freeze and Cherry, 1979; Rushton, 2003 and Vick, 1990). As described in Vick (1990), this form of assessment focuses on the performance of the dam and its immediate surrounds and does not represent the entire facility or the regional flow system of which it is part. Hydraulic performance assessments can also be used at the design stage to understand the size requirements and the performance of the sub-base drainage or toe drains and to understand the efficacy of liners in mitigating leakage from the facility. The objective of the early design assessment is often to optimise designs to identify the most cost-effective solution, which will meet the design requirements.

From an environmental perspective, national legislation and international guidelines place increasingly stringent requirements on developers and operators to mitigate environmental impacts associated with TMFs. In Europe, the Mining Waste Directive (Directive 2006/21/EC on the management of waste from the extractive industries) (EU, 2006a) requires that leachate quality from the TMF is assessed, leachate production is minimised and pollution of groundwater or surface water as a result of discharge from the facility is prevented. Developers and operators must demonstrate use of Best Available Techniques (BAT) as described in the European Commission BAT Reference (BREF) document (EC, 2009). The International Finance Corporation (IFC) Performance Standards also require developers and operators to avoid, minimise, or control the release of pollutants from mine facilities (IFC, 2012). Hydraulic performance assessments allow estimation of leakage and therefore mass loading to groundwater from a

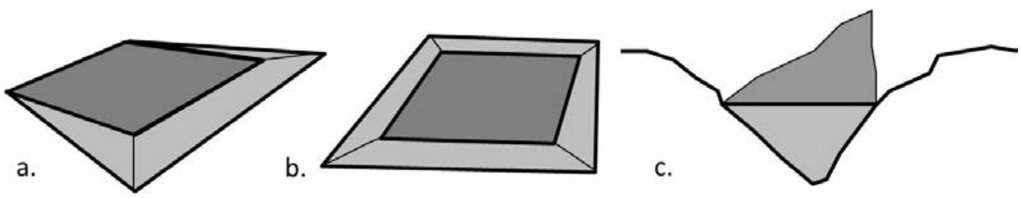


Figure 1 *Illustration of standard TMF surface containment structures: a. side of hill impoundment, b. ring dyke impoundment, c. cross valley impoundment.*

facility, and potential impacts on receiving water courses, allowing developers to demonstrate that proposed designs are appropriate with respect to impact on the water environment. This problem is significantly different to impounding embankment design problems and has received less attention historically. The increasing requirement for low permeability basal liners in TMFs has also increased the complexity of such assessments.

There is a distinction between the information required to adequately represent flow in the embankment, drain and liner design assessments and that required for the investigation of environmental problems associated with TMF seepage. Recognition and consideration of this distinction is considered key in developing appropriate assessment solutions. It is the experience of the authors that local scale assessments intended for embankment design are often misapplied in discussions of the management of seepage, and efficacy of liners in mitigating seepage from the TMF as a whole, although such assessments typically are not able to accurately represent the boundary conditions controlling the flow systems or significant components of the flow system under consideration. The objective of this paper is to illustrate how dimensionality and scale are fundamental in numerical modelling approaches to TMF hydraulic performance assessment and to present two case studies illustrating the advantages and limitations of typical 2-D and 3-D approaches.

Basal Liners In TMF Environments

In order to mitigate environmental impacts from TMFs and/or to comply with local, national or international legislation, it may be necessary to line all or part of the facility to reduce leakage rates and potential impacts on downstream groundwater and surface water. In Europe, the requirements of the Mining Waste Directive (2006/21/EC; EU, 2006a), the Water Framework Directive (2000/60/EC; EU, 2000) and associated Groundwater Daughter Directive (2006/118/EC; EU, 2006b) are leading to the lining of tailings facilities, such as the Lisheen mine in Ireland, the largest lined tailings facility in Europe (Dillon et al, 2004). As with other waste disposal applications, lining systems may comprise natural clay materials, geosynthetic clays (GCL), geomembranes or a combination of material types. A hydraulic barrier may also be constructed from fine tailings materials, often referred to as 'slimes' (United States Environmental Protection Agency, 1994), although modern legislation would require these materials to be chemically inert.

The hydraulic performance of engineered lining systems in disposal facilities is well characterised as a result of work on municipal waste disposal sites over the past 25 years (e.g. Rowe et al, 2004; National Research Council, 2007). In particular, this body of work has developed methods to represent rates of leakage through geomembrane liners, where leakage occurs through defects rather than as porous flow. However, a number of key issues distinguish the behaviour of liners in tailings facilities from those in municipal waste disposal facilities:

- Tailings may have widely varying hydraulic conductivity ranging from 10^{-6}m/s to less than 10^{-10}m/s (Vick, 1990), but commonly have low hydraulic conductivity following consolidation (often <$5x10^{-8}$m/s) such that, as noted in the EC (2009) reference document, the consolidated tailings provide the primary control on leakage rates;
- The common use of valley settings for TMFs, combined with the large extent of the facilities, often render groundwater heads beneath the liner spatially variable; this, combined with restrictions on fluid migration above the liner due to the low tailings permeability, often renders TMF problems unsuitable for analytical approaches to leakage calculation;
- Typically, engineered (above liner) basal drainage systems are not present in tailings facilities such that head on the liner may be high;
- The chemistry of the tailings effluent may increase the permeability of GCLs (Shackleford et al, 2010); and
- Temperatures are typically lower in TMFs than municipal waste sites where biological activity raises temperatures within the waste. This will slow the rate of geomembrane degradation in TMFs in comparison with municipal waste sites, but degradation of the liner over time will still occur.

Hornsey et al (2010) propose that at low temperatures, the effects of acidity, high sulphate concentrations and hypersalinity on the strength of geomembrane liners (and therefore rate of defect occurrence) can be managed through appropriate design and material selection. Little published information is currently available regarding the rate of defect generation in geomembrane liners in TMFs, or the longevity of liners in TMF environments.

Approaches To Hydraulic Performance Assessment

Analytical approaches exist to represent a number of aspects of the hydraulic performance problems outlined above. Phreatic surfaces within TMFs and tailings embankments have historically been estimated using flow nets (Freeze and Cherry, 1979). However, this approach has been largely replaced by numerical modelling, which is greatly more flexible in heterogeneous environments, and less prone to human error. Leakage through a clay liner or GCL can be estimated using Darcy's Law for fixed head saturated conditions. Similarly, a range of empirical relationships have been published to calculate leakage through defects in geomembranes under different construction, sub- and supra-liner conditions. Lupo (2010) provides a summary of the key equations and the approaches are discussed in National Research Council (2007). Rowe (2005) concludes that actual recorded leakage rates from constructed facilities studied were orders of magnitude higher than expected for conditions with a good, or even poor, contact between the liner and underlying material, and that the empirical equations could only be validated against recorded flows if wrinkles were present in the liner.

However, analytical approaches are not readily adapted to situations where a simultaneous solution is sought for more than one problem objective (typically, both design and environmental impact assessments would require calculation by analytical methods of a number of inter-dependent elements to understand the entire flow system). Furthermore, variably saturated flow conditions develop both within and below TMFs during operation, particularly in valley fill scenarios. Beneath the TMF, groundwater heads are likely to be spatially variant due to the original change in water table elevation across the valley, and will change with time as a result of tailings deposition and seepage from the TMF. Within the TMF, the degree of saturation of the tailings varies as the location of deposition moves, and as tailings distal to the disposal point drain and consolidate. The tailings may potentially be unsaturated at the base and saturated nearer to the surface, in addition to containing saturated zones in the vicinity of the decant pond and unsaturated areas around the facility perimeter. The degree of saturation of soils or rock underlying the facility will change with time as seepage from the facility saturates the underlying ground. Following cessation of operation, depending on the climate, lining system, tailings permeability, foundation permeability and rate of infiltration to the tailings, the tailings may drain completely, or may remain saturated. Spatial variation and variably unsaturated conditions render TMFs highly unsuitable for the application of analytical solutions, which typically require homogeneous, saturated conditions. Numerical modelling approaches to hydraulic performance calculations are preferable, even in preliminary calculations at feasibility or scoping stages of development, as they provide greater flexibility, introduce greater realism and therefore have the ability to provide a more accurate representation of the problem.

Numerical Modelling Approaches

At scoping and feasibility stages of mine development, modelling of seepage and flow for a range of design scenarios can be used to place bounds on the impacts of remaining uncertainties on aspects of the design, assist in design decisions and assist in optimisation of the design to identify the most effective solution. These problems are frequently conceptually simple from a hydraulics perspective, but may involve assessment of variation in material properties of design components at a scale that is small in the context of the entire TMF and surrounding regional groundwater flow regime. Appropriate models simplify the representation of flow to include only those aspects that are most significant at the scale of interest, facilitating modelling at a scale small enough to represent key elements of the design in a detailed fashion.

Where the objective is to assess seepage from the entire TMF and its impact on groundwater and surface water downgradient, this is a problem of greater scale, encompassing elements of the regional groundwater flow field and groundwater recharge and discharge zones. Greater effort must be expended in understanding and representing the regional groundwater flow system in modelling. Vick (1990) notes that traditional geotechnical approaches to assessing seepage and phreatic surface location for stability purposes are not adequate to quantify either seepage from the facility as a whole, or the fate of contaminants in groundwater. Spitz and Moreno (1996) describe how the art of model selection is to identify the simplest modelling approach that is able to capture the key processes influencing the system under consideration, whilst minimising the modelling effort required.

A key consideration at the outset of the numerical modelling exercise is to determine the number of dimensions that are required to adequately represent the flow system under consideration. Spitz and Moreno (1996) provide a more extensive discussion of the key concepts illustrated here.

In unlined TMFs in hot, arid environments situated significantly above the water table, seepage to groundwater from the TMF is primarily controlled by the water balance at the surface of the tailings, where high evaporation rates combined with a high capillary fringe in fine-grained tailings may result in significant evaporative losses, reducing net infiltration into the body of the tailings to a minimal amount. In these conditions, a simple 1 dimensional column water balance model (using software codes such as UNSAT-H or HYDRUS-1D) is sufficient to estimate total seepage from the facility.

Simulation of phreatic surface and dam seepage for TMF designs typically rely on 2-D profile unsaturated flow models, which represent cross-sections of the dam and immediately surrounding area. Two dimensional models of this type are useful as they enable representation of both the vertical and horizontal components of flow associated with infiltration and percolation into the tailings, flow through and under the embankment and discharge at the dam toe. Furthermore, delineation of the component materials in the dam core and walls, in the tailings, and in any basal liner in addition to underlying geology within the model is greatly simplified when considered in only two dimensions, such that accurate representation of the design geometry is possible without requiring an excessive number of grid nodes (and associated computational demands) or excessive time to develop the model. Application of such models is appropriate where the dominant regional groundwater flow direction is parallel to the line of section and uniform, and where, at the scale of assessment, flows in the third dimension are not significant. A range of suitable software codes are available adapted to this type of modelling, including codes such as Geostudio SEEP/W and VADOSE/W, Soil Vision, FLAC, FEFLOW and MODFLOW-SURFACT. Such models can be quick and relatively simple to construct utilising material design specifications and data from standard testing on tailings materials and can be readily modified to consider a range of design options providing a powerful means of rapidly assessing design scenarios.

Vertical flows within and out of the TMF are key components of the hydraulics of a TMF environment. Therefore, inclusion of the vertical plane in any numerical modelling assessment is essential to represent key components of the system. This concept is illustrated with respect to the flow from the TMF in Figure 2.

The position of the phreatic surface and seepage from ring-dyke and side of hill impoundments can reasonably be approximated by two dimensional systems provided that:

- the ring dyke impoundment is underlain by unsaturated conditions, or if saturated causes groundwater mounding and radial flow in the underlying groundwater flow system or has an insignificant effect on regional groundwater flow; and

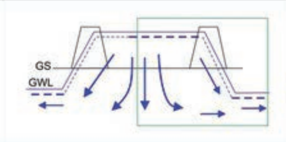
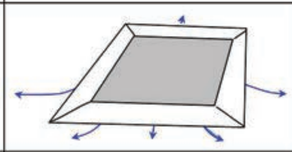
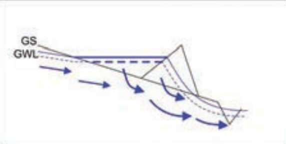
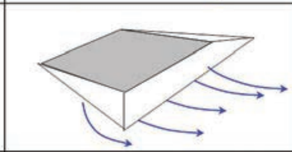
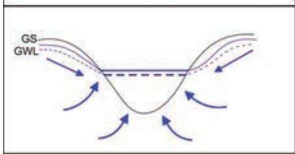
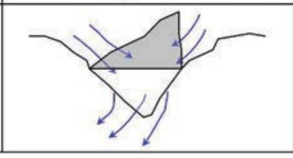
2-D Representation (After EC, 2009)	3-D Representation	Applicability
		**Ring dyke:** radial flow geometry, flow system well represented by 2-D section from centre to perimeter
		**Hill slope:** Gravity flow to point is discharge at base of slope, 2-D geometry is representative of key elements of flow.
		**Valley fill:** Discharge to valley centre (into tailings) and downslope parallel to natural valley. 3-D flow system, flow to downstream receptors not represented in 2-D.

***Figure 2** Illustration of flow dimensions in ring dyke, side of hill and cross-valley TMFs. Water flow direction away from the facility is illustrated by blue arrows.*

- regional groundwater flow beneath the hill slope impoundment is approximately parallel to the direction of slope.

Seepage from the side of hill facility can be estimated by multiplying the seepage in two dimensions by the facility width perpendicular to the hill slope. Seepage from the ring dyke facility can be estimated by multiplying seepage in a 2-D section from the centre to the facility perimeter, by the facility perimeter. In the valley fill scenario, groundwater flows into the facility from the valley margins, and discharges along the line of the valley centre creating a three dimensional flow field. Groundwater head beneath the facility will vary across the valley, whilst head within the TMF will dissipate down the valley. This scenario cannot be appropriately simulated in two dimensions. Furthermore, in valley scenarios, the local groundwater flow regime is likely to be parallel to the valley side slopes, discharging to a central stream or river, whilst regional groundwater flow may be perpendicular to the orientation of the stream flow, mirroring regional drainage.

In scenarios where facilities are underlain by an unsaturated zone and the underlying groundwater flow system can be regarded as a one dimensional flow field, seepage from side of hill or ring dyke facilities estimated using 1-D or 2-D models may be used to simulate contaminant transport in 2-D profile models representing flow from the facility to the nearest surface water course (similar to the conceptual flow system illustrated in Figure 3). Valley fill TMFs, due to deposition at a location with natural groundwater discharge, will rarely be significantly above the water table, and therefore require more detailed consideration in three dimensions to represent discharges to surface water downstream of the facility. This is also true where the facility causes groundwater mounding or is underlain by saturated conditions.

Three dimensional models, constructed in numerical modelling packages such as MODFLOW-SURFACT or FEFLOW, typically require more data to construct and calibrate than a 2-D profile model, and often require greater computational effort. Though more onerous, a 3-D approach is required where 2-D models would neglect significant elements of the flow system, and would not accurately represent the boundaries controlling flow through the system. A 3-D modelling approach can still encompass varying degrees of complexity depending on the objective and requirements of the problem. Ultimately, in the final design stages, a detailed regional scale, calibrated model representing the natural hydrogeological system will be required. However, at

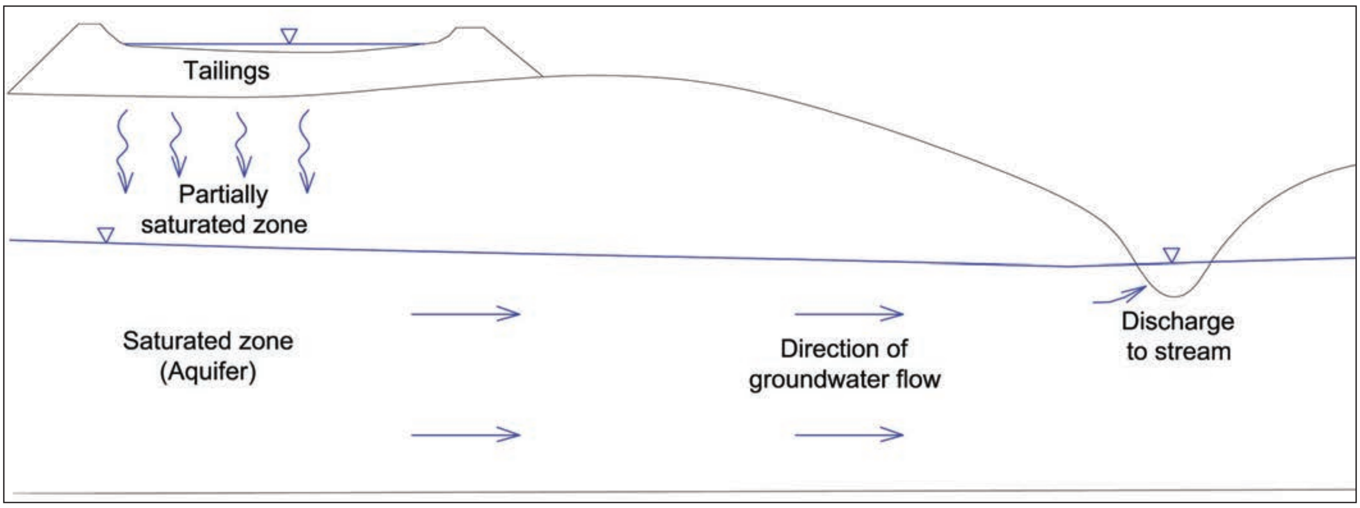


***Figure 3.** Illustration of a 2-D representation of contaminant migration from an above water table TMF to a nearby water course, after Vick (1990).*

early stages, a 'sand box' model with simplified geology and boundary conditions may be appropriate, providing a solution that is more accurate than an analytical problem approach, but does not require data to describe all details of the natural system.

Two case studies described below illustrate the application of appropriate modelling approaches to facilitate decision making in two TMF design problems. The first case study illustrates the use of a 2-D numerical unsaturated flow model to assess drainage requirements for the remediation of a failed basal liner at a ring-dyke impoundment situated on a valley flank. The second case study illustrates the use of a 3-D numerical unsaturated flow model to assess the performance of a range of basal liner designs for a proposed valley fill TMF in comparison to an unlined construction.

Case Study 1: 2-D Assessment

Following failure of the basal liner of a TMF, shortly after completion of its construction and before significant quantities of tailings had been deposited, a seepage assessment was undertaken to support the remedial design. The original liner design comprised a 1mm thick high density polyethylene (HDPE) membrane over compacted loam, and the principal cause of the failure was related to the failure of a drain constructed beneath the TMF.

Higher than anticipated flows in the drain and the lack of a geotextile filter were judged to have enabled the mobilisation of fines in the loam layer, clogging the main under drain and creating voids beneath the liner, possibly in combination with high pore pressures and resultant basal heave. The remedial scheme included raising the base of the TMF, relining the base with new compacted loam and installing a geotextile filter layer and a 1.5mm HDPE liner (Figure 4), in addition to replacing the drain.

The objectives of the assessment were to assess the following:

- Anticipated flows to the main drain beneath the facility following remediation to assist in drainage design;
- Pore water pressures within and under the existing structures;
- Pre-existing seepage; and
- Changes in pore water pressure and the potential for future seepage based on the construction of the remedial design.

The facility comprises a ring dyke impoundment situated on a shallowly sloping portion of the flank of a valley. Local groundwater flow in the vicinity of the ring dyke is parallel to the modelled line of section, and the drain associated with the failure runs approximately perpendicular to the direction of local groundwater flow (and the line of section). The drain represents a linear boundary, which can adequately be represented in two dimensions, superimposed on a local groundwater flow regime which can be approximated to a one dimensional flow system at the scale of interest. A two-dimensional modelling approach was considered appropriate to adequately represent the key elements of the local flow system in the context of the objectives of the assessment, and also facilitated a detailed representation of the lining system in the original and remediated scenarios. Steady state seepage analysis was carried out using GeoStudio 2007 SEEP/W (Geo-slope International, 2007), a two-dimensional finite element code widely used in the calculation of seepage through embankment structures.

A cross section was modelled under three steady state scenarios to simulate various lifecycle stages as follows:

- *Pre-failure conditions.* A 5m depth of water present in the void and the limited amount of material present at the time of liner failure omitted;
- *Remediated conditions (immediately post-completion).* Maximum seepage scenario with the void allowed to flood to an elevation 1m below the embankment crest. Layers of geotextile material assumed to have a high hydraulic conductivity compared to other lining materials omitted; and
- *Remediated (long term).* The TMF assumed to be full and tailings represented explicitly. A limited area of open water (decant pond) assumed at 1m below the embankment crest. As in the post-completion scenario, layers of geotextile material assumed to have a high hydraulic conductivity compared to other lining materials omitted.

The rate of water passing through an HDPE liner is highly dependent on, amongst other things, the size and

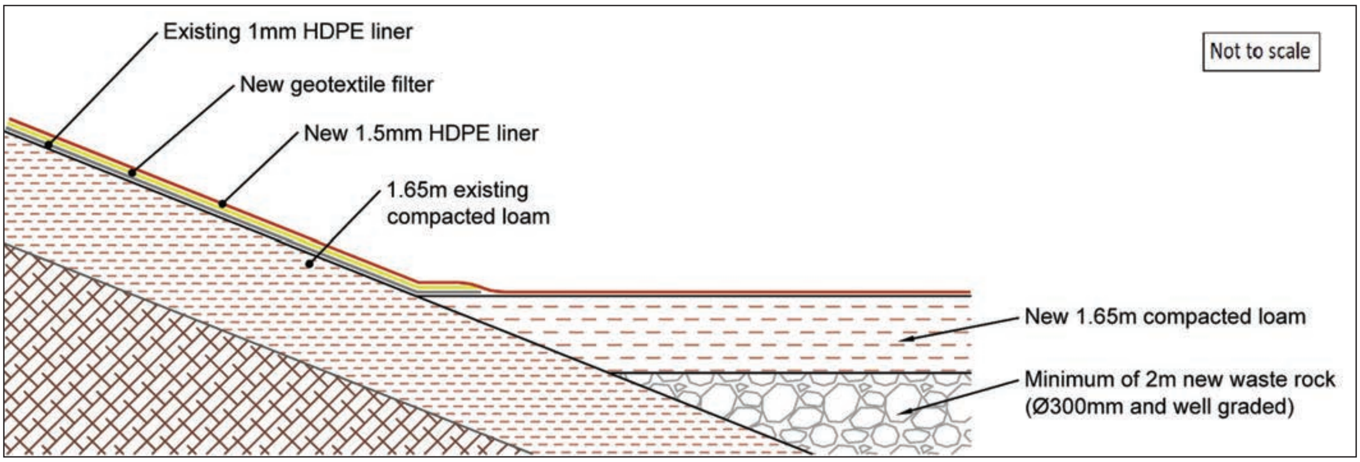


Figure 4. *Section through the base of the TMF.*

number of defects (either caused during construction or occurring long term) over which there is significant uncertainty and little published information, as noted earlier. The basal HDPE liner was therefore simulated assuming an equivalent porous medium with a hydraulic conductivity based on scoping calculations carried out using the empirical method provided by Giroud (1997) incorporating an assumed head, an assumed number of defects and a range of construction quality standards; uncertainty over the resultant equivalent hydraulic conductivity of the membrane was explored through sensitivity analysis. Sufficient research is not currently available to quantify the chemical effects of tailings on HDPE membranes, and therefore this aspect was not considered in the study.

Calculated seepage rates assuming representative widths for the base of the site and the drainage runs are presented in Table 1. The results of sensitivity analysis in which the equivalent hydraulic conductivity of the HDPE liner was varied by an order of magnitude either side of the originally assumed value are shown in brackets.

The 2-D modelling indicated potential flows of up to approximately 50l/s entering the drainage system beneath the TMF following remediation, confirming that the original drain capacity may have been insufficient.

Case Study 2: 3-D Assessment

To support decision making at the design stage for a proposed TMF, a comparative assessment of the hydraulic performance of four alternative containment scenarios was undertaken using the 3-D groundwater modelling code MODFLOW SURFACT-Flow. The objective of the study was to investigate the relative efficacy of the engineering alternatives in limiting leakage from the facility and discharge to a downstream water course, rather than to provide accurate estimates of potential leakage rates.

The proposed TMF is a valley fill design with an area of approximately 3km^2 and is surrounded by steep topography. Under current conditions a watercourse flows through the centre of the site and groundwater discharge occurs in the valley floor. The TMF is underlain by alluvial deposits in the vicinity of the river and by colluvium overlying sedimentary bedrock in the north of the area and volcaniclastic bedrock in the south. Preliminary testing indicates the tailings to be of relatively low hydraulic conductivity, in the range 1x10^{-8}m/s to 1x10^{-9}m/s. Given the site setting, it was concluded that a three dimensional model was required to fully represent the interaction between the TMF and surrounding groundwater flow regime, which is a strong control on leakage from the facility.

A baseline (no TMF) steady state MODFLOW-SURFACT-Flow model was created for the TMF domain by telescoping an existing steady state regional MODFLOW model. Telescoping is the process of extracting and refining a section of a larger model utilising heads and flows calculated by the larger, lower resolution, model to provide boundary conditions for the localised refined model. The model boundaries were defined based on topography and groundwater contours calculated by the regional model. This calibrated model was modified to assess four containment scenarios:

1. A HDPE liner on the upstream dam face only, otherwise unlined;
2. A HDPE liner across the entire TMF footprint;
3. A composite (GCL and HDPE) liner across the entire TMF footprint;
4. Unlined with a grout curtain beneath the TMF.

Each comparative model scenario considered the final maximum TMF extent in steady state. The grout curtain was represented as a zone of lower hydraulic conductivity to 30m depth. For the three scenarios reliant on a geomembrane liner (GML) (single and composite) the GML was represented as a 1m thick porous layer with a transmissivity equal to the GML under approximated head conditions, an assumed number of defects and differing construction quality assurance (CQA) standards (Environment Agency, 2004). The hydraulic conductivity of the modelled porous liner was estimated through equivalence to the maximum potential leakage through defects under an equivalent head; an approach that is considered to be a reasonable approximation for flow modelling, although not suitable for contaminant transport modelling, discussed further in Digges La Touche and Garrick (2012). Calculated equivalent hydraulic conductivity values for the modelled liner in Scenarios 2 and 3 above are shown in Table 2.

The equivalent hydraulic conductivity of the composite liner increases as head in the tailings increases, such that it is highest where the tailings are thickest and beneath the decant pond (note this is the

Scenario	Representative Widths (m) *(base / drains)*	Seepage through base of TMF (l/s)	Inflow to drain beneath TMF (l/s)	Inflow to drain beneath TMF eastern embankment (l/s)
Pre-Failure	90 / 200	4	5	9
Remediated, Post Completion	200 / 200	46 (9-64)	33 (7-45)	15 (7-20)
Remediated, Long Term	200 / 200	0.2	0.8	4.4

Table 1. *Calculated seepage rates (values in brackets represent the range of sensitivity analysis results).*

Head (m)	Equivalent liner permeability, single GML (m/s)	Equivalent liner permeability, composite liner (m/s)
"Excellent" CQA		
65	8.40×10^{-11}	2.40×10^{-11}
50	9.60×10^{-11}	1.91×10^{-11}
35	1.15×10^{-10}	1.40×10^{-11}
20	2.80×10^{-10}	8.50×10^{-12}
5	4.32×10^{-10}	2.32×10^{-12}
"Good" CQA		
65	$5.00\text{x}10^{-7}$	$6.40\text{x}10^{-10}$
50	$5.70\text{x}10^{-7}$	$5.10\text{x}10^{-10}$
35	$6.72\text{x}10^{-7}$	$3.80\text{x}10^{-10}$
20	$8.70\text{x}10^{-7}$	$2.30\text{x}10^{-10}$
5	$1.52\text{x}10^{-6}$	$6.50\text{x}10^{-11}$

Table 2. *Calculated liner equivalent hydraulic conductivity values for Scenarios 2 and 3, defect occurrence rates based on "good" and "excellent" CQA (Environment Agency, 2004).*

reverse of the behaviour of a single membrane liner placed on a permeable substrate). Figure 5 illustrates the head-dependent spatial distribution of hydraulic conductivity in the composite liner scenario.

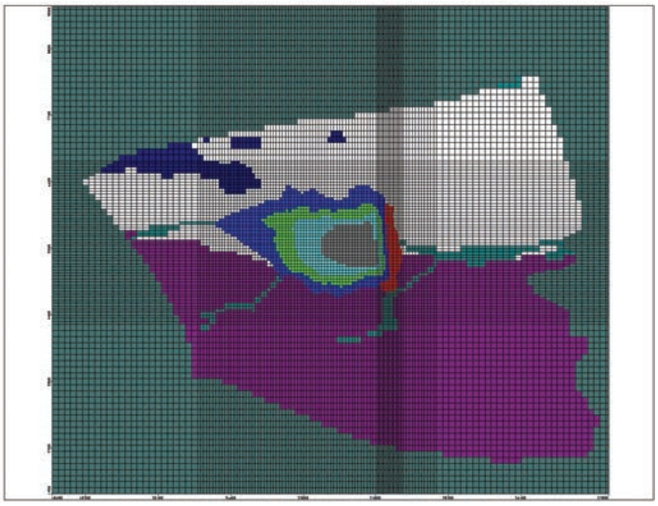


Figure 5. *Hydraulic conductivity zones in the composite liner scenario MODFLOW-SURFACT model, the TMF is in the centre of the model.*

Comparative leakage rates under the four assessment scenarios are presented in Table 3. The models demonstrated that a >98% reduction in leakage could be achieved with excellent construction standards using a composite liner, retaining an additional 20% of the total potential leakage in comparison with a single HDPE liner with similar construction standards.

The performance of HDPE liners is extremely sensitive to defect occurrence rates, linked to manufacturing and construction quality. The assessment therefore indicated a high sensitivity to the construction quality of the HDPE liner, showing that in scenarios with low tailings permeability, a HDPE liner requires construction to the highest standards to be of benefit. As illustrated in Table 2, with 'good' rather than 'excellent' CQA standards (as defined in Environment Agency (2004)), the single HDPE liner is estimated to be more than an order of magnitude more permeable than the overlying tailings; leakage from the facility with this liner would be controlled by the permeability of the tailings, not by the underlying liner, resulting in leakage as in the 'unlined' case above. In comparison, a composite liner with 'good' CQA standards would still be considerably less permeable than the overlying tailings, but an order of magnitude more permeable than the 'excellent' case. A ten-fold increase in leakage from the 'excellent' composite liner case in Table 3 equates to 18% of the base case leakage rate.

Scenario	Reduction in steady state leakage achieved in comparison with unlined case (%)	Increase in steady state surface discharge outside the TMF within model domain in comparison with base case (No TMF) (%)
Unlined (u/s dam face lined)	-	691%
Single HDPE liner	77.1%	210%
Composite liner	98.2%	2%
Unlined with grout curtain	-0.2%	693%

Table 3. *Summary of comparative leakage assessment results ("excellent" CQA).*

Leakage is also highly sensitive to assumptions regarding tailings permeability and anisotropy (which are typically based on limited sampling) and assumptions regarding recharge to the surface of the TMF in active and inactive beach areas, which are necessarily derived from available water balance data.

As anticipated, the grout curtain had minimal influence on leakage rates from the facility or on rates of groundwater seepage in the valley downstream of the TMF.

The methodology described here is considered a robust method for completion of a comparative performance assessment. Application of a similar methodology to assess leakage from the TMF in absolute terms is a considerably more complex problem, requiring consideration of the highly transient hydraulic system within the TMF during and following operation including: the accumulation of tailings and transient changes in infiltration rate, decant pond extent and elevation, head/saturation within the TMF during its life, and the longevity of plastic liners in a TMF scenario.

Discussion

The case studies presented above are considered by the authors to represent appropriate modelling approaches to the hydraulic performance assessment of proposed construction designs in two TMF environments. In each case, the models do not fully represent the real world; the models are steady state flow solutions, based in the first case on a range of life cycle states, and in the second case on the final TMF geometry. TMFs are highly transient systems for a number of reasons as follows:

- Tailings are deposited in a saturated state such that, provided capacity of discharge from the tailings exceeds infiltration, they typically drain and consolidate with time.
- Tailings permeability is typically low, such that TMFs respond slowly to changes in hydraulic stresses and are liable to take many years to reach steady state flow conditions. In fact, facilities frequently may not reach steady state flow conditions until many years after closure.
- As the facility develops, leakage from a TMF is often limited by the permeability of the tailings rather than underlying materials (as identified in Case Study 2, above); however, the thickness of tailings increases with operational life and this condition may not occur until the later stages of operation.

It is therefore unlikely that the steady state models discussed accurately quantify the (transient) flow rate from the facilities at any point in their operational or post-closure life, as continuously changing conditions during operation and alteration of the facility geometry and engineering at closure may prevent the modelled steady state flow conditions being achieved. This does not prevent the models being valuable assessment tools which, through use of a range of steady state scenarios which capture 'peak' flow events or comparative engineering performance, are appropriate to the problems they were developed to address.

In each case, the modelling approach has been selected to be as simple as practicable to represent key elements of the flow regime, such that the models did not require extrapolation beyond the limits of available data and were computationally efficient. In the first case study, transience in the system was addressed through consideration of a number of life cycle states and a 'worst case' scenario based on the conditions of the historical failure was considered. In the second case study, the objective was a comparative performance assessment rather than prediction of actual rates of leakage at any point in time; therefore, the approximation to steady state conditions did not affect the validity of the interpretation of the model results to inform the design decision. As the design process moves forward, or objectives change, more detailed transient modelling approaches may become necessary to meet new objectives, particularly where those objectives are to quantify surface water impacts arising from discharge from the facilities.

Conclussion

The estimation of the position of the phreatic surface within embankments of surface tailings impoundments is an essential, and therefore routine, element of TMF design. Increasing focus on environmental impacts of tailings facilities internationally and changing regulations have made both environmental impact assessments and construction of fully lined TMFs increasingly common. This change has increased the range of situations where hydraulic performance assessments of TMFs are required, particularly to quantify leakage rates and the efficacy of design measures to limit leakage.

Many approaches exist to quantify saturation, pore water pressures, the position of the phreatic surface and sub-surface water flows in natural systems. The complexity of TMF environments, including spatial and temporal variation in heads driving flow within and beneath the facility and the dominance of low permeability tailings in restricting discharge from the base of TMF facilities, renders common analytical solutions to flow problems unsuitable for the hydraulic assessment of TMFs. Numerical models are typically applied and are preferable in the assessment of the hydraulic performance of TMFs because they provide much greater flexibility and can be used to more realistically approximate actual conditions.

Numerical modelling will always require a simplification of real life environments and the approach and software selected for an assessment should be appropriate to reflect key processes occurring within the flow system, whilst being computationally efficient. Many local scale TMF design problems may be appropriately represented by 2-D vertical profile models, which capture key vertical flows associated with infiltration into the tailings, flow beneath and through embankments and discharge at the embankment toe. However, larger scale environmental impact problems typically require representation in 3-D to capture boundaries to regional flow systems and discharge to key receptors. Furthermore, in cross valley TMF geometries, localised groundwater and tailings flow systems are three dimensional and cannot be approximated to two dimensions.

With appropriate approximation and simplification, numerical modelling can provide powerful and cost-effective solutions to hydraulic and hydrogeological design and performance problems. Two case studies are presented where appropriate groundwater modelling assisted in design decision and provided valid and informative conclusions regarding behaviour of the flow system whilst representing a simplification of the complex, transient flow system actually occurring within an operational TMF. Understanding of the impact of assumptions used to simplify real world systems is a key element of successful flow modelling, and is no less important in hydraulic performance of TMFs environments. Models developed for specific geotechnical design problems may not be suitable for assessment of seepage impacts from a tailings facility as a whole and care should be taken in selecting a modelling approach appropriate to the problem objective and TMF setting and geometry in TMF assessments.

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