Hydraulic performance of liners in tailings management and heap leach facilities

Gareth Digges La Touche[1], Hollie Garrick[2]

[1]*Golder Associates, Attenborough House, Browns Lane Business Park, Stanton-on-the-Wolds, Nottinghamshire, NG12 5BL, United Kingdom, garethdlt@golder.com*
[2] *Golder Associates, Attenborough House, Browns Lane Business Park, Stanton-on-the-Wolds, Nottinghamshire, NG12 5BL, United Kingdom, hgarrick@golder.com*

Abstract

The use of lining systems to manage the risks from leachate in tailings management and heap leach facilities is common practice. However the relative hydraulic performance of such lining systems is often misunderstood with consequent design and environmental risk implications. This paper examines the hydraulic performance of different lining systems and the longevity of such systems during the life of mine. A series of tools are described and discussed to illustrate the performance assessment processs.

Keywords: tailings, heap leach, lining, liner, permeability, transport

Introduction

Leachates produced from both heap leach facilities for ore processing and from tailings resulting from extractive ore processing typically contain substances that are hazardous to the environment. Heap leach facilities typically are constructed on lined pads and circulate cyanide or sulphuric acid solutions to extract the target metal from the ore, with the aim being to capture the leachate generated for further processing prior to recirculation back through the heap. The management of tailings often comprises storage within a contained facility where the water content of the tailings slurry can evaporate, or to a lesser extent infiltrate to ground, leaving behind a solid waste. Where heap leach facilities are commonly constructed on lined pads, tailings have, historically, been deposited directly onto natural ground contained behind a dam. However, with the advent of legislation, particularly in Europe, to protect the environment following the failures of the Aznalcóllar (1998) and Baia Mare (2000) tailings dams (Amezaga and Younger 2006) tailings are now often, in some jurisictions, managed within lined engineered facilities.

This paper examines the differences in performance between a compacted clay liner (CCL) or geosynthetic clay liner (GCL) and a geomembrane liner (GML) and practical methods for assessing the performance of GMLs in numerical flow and transport models such as SEEP/W, MODFLOW and FEFLOW. The methods for assessing the hydraulic performance of lining systems have largely been developed through studies on the performance of landfill lining systems (e.g. Giroud and Bonaparte 1989a and 1989b, Giroud 1997, Rowe et al 2004 and US National Research Council 2007). A summary of lining system design using GMLs for heap leach facilites, with particular emphasis on material compatibility, is presented in Lupo 2010 and a review of the effect of leachates from tailings and heap leach facilities on GMLs is presented by Hornsey et al 2010. Note is also made of the need to account for the change on liner performance with time.

Liner life

Changes in the hydraulic properties of CCLs over time are widely accepted to be primarily attributable to mechanical effects: compaction from the overlying load, puncturing and differential settlement (e.g. US National Research Council 2007). Whilst some studies have indicated that chemical incompatibility may result in changes in clay structure, porosity and permeability in specific environments (e.g. in contact with leachates which are very acidic or contain high concentrations of hydrophobic organic compounds), CCLs are generally considered chemically stable and as a result the permeability properties of a CCL effectively remain constant with time. The same is true of GCLs, although studies have indicated that the hydrated permeability of such liners is a function of the ionic strength of the liquid saturating the liner (e.g. Kolstad 2000).

In comparison, GMLs degrade with time as a result of oxidation and breakdown of the liner material, resulting in an increase in leakage with time under constant head conditions. This process is dependent on temperature and conditions surrounding the liner, but at ambient temperatures (15°C to 30°C), is estimated to take hundreds of years. The Environment Agency of England and Wales (2004) report the onset of degradation after 900 - 1300 years at 20°C while the US National Research Council (2007) report a service life of 565 - 900 years at 20°C. Based on the Environment Agency's preferred assessment method for landfill liners (Environment Agency, 2003 and 2004), the following approach may be considered appropriate:

It is assumed that when laid a GML has few defects but that the number increases in a linear manner due to damage during construction and operation. Published defect rates such those reported in Environment Agency 2004 may be used to define defect frequency. The number of defects may be considered to remain constant until the onset of oxidation of the GML (the formation of stress cracks is neglected); and after the onset of oxidation the area of the holes is considered to double on a half life basis until the membrane no longer inhibits leakage (leakage is controlled by the underlying clay liner).

As a result of degradation, the leakage rate through the GML is time variant and under constant head conditions will resemble the time history illustrated in Figure 1. This time variance has a profound effect on the long term environmental impact of facilities reliant on GML lining systems.

Calculation of seepage through a clay liner

Seepage through a CCL or GCL of known properties can be calculated for conditions of known hydraulic head through the application of Darcy's law ($Q = KiA$, where Q is leakage, i is the hydraulic gradient across the liner and A the basal area of the facility). The hydraulic gradient across the liner can be calculated based on the head difference between the saturated fill and underlying material, if saturated. If the liner is underlain by unsaturated material, consideration should be given to the interval over which head loss occurs and it may be appropriate to simulate leakage using a numerical variably saturated flow model.

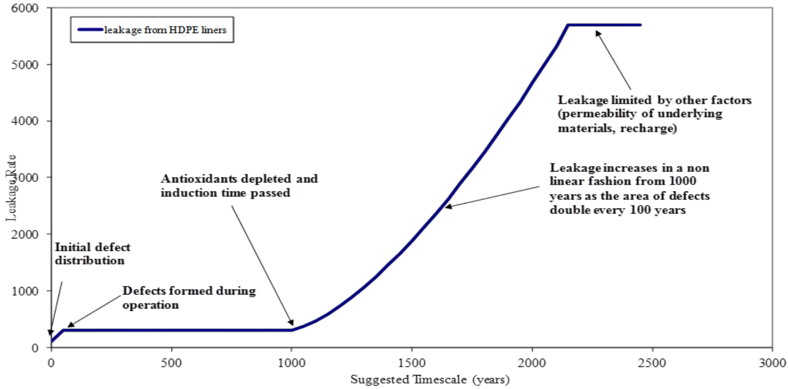

Figure 1 *Illustration of time variant leakage through a GML under constant head*

Calculation of seepage through a geomembrane liner

Seepage through GMLs under constant head conditions is governed by the frequency of occurrence of defects in the liner, the permeability of the underlying material, the hydraulic gradient across the liner and the contact between the membrane and underlying materials. The frequency of occurrence of defects is a function of the liner environment, the quality of the materials and the construction quality assurance measures taken to protect the liner during placement and deposition of the first layers of overlying material (e.g. Environment Agency of England and Wales 2004).

Many analytical and empirical solutions have been published to quantify leakage rates through defects in GMLs and care must be taken in selection of an appropriate approach, which will depend on the physical properties of the system under consideration, the objective of the assessment and the validity of the assumptions on which the solution approach is based. Some examples of problems which have received attention are:

- Calculation of leakage through a GML under constant head (no limitation on liquid supply) underlain by a permeable medium (Giroud and Bonaparte, 1989);
- Calculation of leakage through a GML under constant head (no limitation on liquid supply) underlain by a low permeability medium (Giroud, 1997);
- Calculation of leakage through a GML overlain and underlain by high permeability media, where flow to the defect is limited by the permeability of the saturated media overlying the defect, resulting in deflection of the piezometric surface in the vicinity of the defect (Giroud, Khire and Sodermann, 1997); and

- Calculation of leakage with (a) varying defect geometries and (b) varying degrees of contact between the GML and underlying material (e.g. (a) Touze-Foltz and Giroud 2003 and 2005, (b) Rowe 1998).

Assessment of Liner Performance in Tailings Management and Heap Leach Facilities

Assessment of seepage from lined tailings management and heap leach facilities is often complicated by the presence of low permeability fill materials overlying the basal liner, such that the overlying material is not free draining and seepage is controlled by the rate of percolation through the tailings, rather than hydraulic head on the liner. In such a scenario, even if the water level within the tailings is known, leakage rates calculated using analytical or empirical solutions described above will only be representative of actual flow rates where the permeability of the liner is significantly lower than that of the overlying tailings, hence leakage rates through the liner are significantly slower than the rate of percolation of water through the overlying tailings. In such instances numerical modelling approaches may be used to understand the interaction between the water balance at the surface of the tailings mass, unsaturated and saturated flow through the tailings, head within the tailings and interaction with groundwater underlying the liner.

The authors of this paper propose a simple, readily applied approach to representing GMLs in numerical seepage (groundwater flow) models. Controls on the hydraulics of the system due to recharge and permeability of the fill and underlying media are assessed within the numerical modelling environment, however preliminary calculations are undertaken to place bounds on the equivalent permeability of the GML to a defined thickness of porous medium on the basis of construction controls and basic liner design, which may then be incorporated in subsequent modelling and sensitivity analysis. The following approach is proposed to obtain an equivalent permeability to allow a GML to represented as an equivalent porous medium in a groundwater flow model:

Defect rates in the GML are estimated for the time period of the assessment using published literature sources (e.g. Forget et al. 2005, Environment Agency of England and Wales 2004) and knowledge of actual or proposed construction standards;

Leakage rates through the GML are calculated using an appropriate empirical or analytical approach:

- For GMLs underlain by low permeability media (a GCL or engineered clay in composite liners, or natural low permeability materials), approaches include the empirical solution of Giroud (1997) or the analytical solution of Rowe (1998).
- For GMLs underlain by permeable media, the Bernoulli equation (e.g. Giroud and Bonaparte 1989) may be appropriate in some circumstances or the approach of Giroud, Khire and Sodermann (1997) at higher heads;
- The equivalent hydraulic conductivity of a clay liner of defined thickness (appropriate to the vertical discretisation of the numerical model) with

equivalent transmissivity under the same hydraulic head is calculated using Darcy's law.

It is noted that the methodology of Giroud (1997) may overestimate leakage rates at high heads. The analytical solution of Rowe (1998) may provide an alternative approach however it requires a parameter, the transmisivity of the GML-clay interface, that is not readily measurable. Given this and that few studies have been completed characterising flow through defects under high heads, the Giroud (1997) approach is considered the best practicable approach to hydraulic performance assessment, even under high heads. It is highlighted that this approach should not be applied in transport modelling due to the difference in attenuation capacity between the simulated porous medium and the GML and the difference in wetted area in the underlying material associated with the two liner types. Kandris and Pantazidou (2012) present a discussion of the performance of various liner designs in the context of contaminant transport.

Example of Application in Performance Assessment

The approach described above has been applied to undertake a comparative assessment of the hydraulic performance of four alternative containment scenarios at a proposed tailings management facility (TMF) using the 3-D groundwater modelling code MODFLOW SURFACT-Flow.

The proposed TMF is a valley fill design with an area of approximately 3.14 km^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 indicated the tailings to be of relatively low hydraulic conductivity, in the range $1x10^{-8}$ m/s to $1x10^{-9}$ m/s.

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; 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:

HDPE liner on the upstream dam face only, otherwise unlined;

- High density polyethylene (HDPE) liner across the entire TMF footprint;
- Composite (geosynethic clay liner and HDPE liner) across the entire TMF footprint;
- Unlined with a grout curtain beneath the TMF.

Each model considered the final maximum TMF extent in steady state. The GML was represented as a 1 m thick porous medium. For the two scenarios reliant on a GML (single and composite) the hydraulic conductivity of the modelled porous liner was estimated through equivalence to the maximum potential leakage through defects under an equivalent head as previously described. The grout curtain was represented as a zone of lower hydraulic conductivity to 30 m depth.

Figure 2 illustrates the head-dependent spatial distribution of permeability in the composite liner scenario

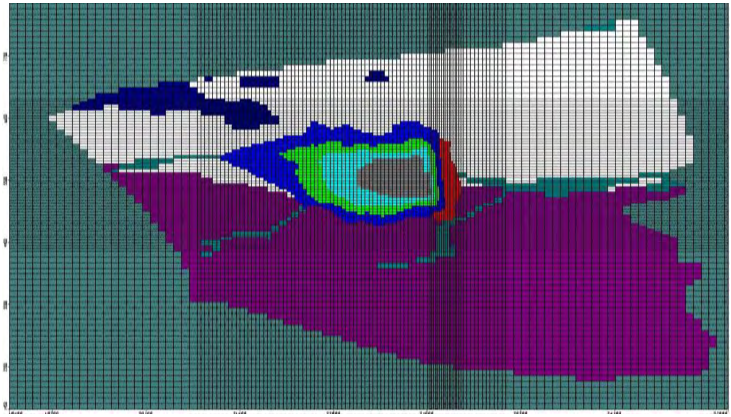

Figure 2 *Hydraulic conductivity zones in the composite liner scenario, the TMF is in the centre of the model.*

The equivalent hydraulic conductivity of the liner decreases as head in the tailings increases, such that it is highest where the tailings are thickest and beneath the decant pond. Calculated equivalent hydraulic conductivity values for the modelled liner in Scenarios 2 and 3 above are shown in Table 1. Results were assessed for "excellent" and "good" construction quality assurance (CQA) standards.

Table 1 *Calculated liner equivalent hydraulic conductivity values for Scenarios 2 and 3, "excellent" CQA*

Head (m)	**Equivalent liner permeability, single GML**	**Equivalent liner permeability, composite liner**
65	$8.40{\times}10^{-11}$	$2.40{\times}10^{-11}$
50	$9.60{\times}10^{-11}$	1.91×10^{-11}
35	$1.15{\times}10^{-10}$	1.40×10^{-11}
20	$2.80{\times}10^{-10}$	8.50×10^{-12}
5	$4.32{\times}10^{-10}$	2.32×10^{-12}

Comparative leakage rates under the four assessment scenarios are presented in Table 2. The models demonstrated that a >98% reduction in leakage could be achieved with excellent construction standards using a composite liner, retaining a further 20% of the total potential leakage in comparison to a single HDPE liner with similar construction standards. However, the performance of HDPE liners is extremely sensitive to defect occurrence rates, linked to manufacturing and construction quality. The assessment 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. Leakage is also highly sensitive to assumptions regarding tailing permeability and anisotropy (which are typically based on limited samples) and assumptions regarding recharge to the surface of the TMF (in addition to leakage from the decant pond), which are necessarily derived from available water balance data. The grout curtain had minimal influence on leakage rates from the facility, or rates of groundwater seepage in the valley downstream of the TMF.

Table 2: *Summary of Comparative Leakage Assessment Results ("Excellent" CQA)*

Scenario	Reduction in Steady State Leakage Achieved in Comparison to Unlined Case (%)	Increase in Steady State Surface Discharge Outside the TMF within Model Domain in comparison to Base Case (No TMF) (%)
Unlined (u/s dam face lined)	-	691%
Single FML	77.1%	210%
Composite liner	98.2%	2%
Unlined with grout curtain	-0.2%	693%

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: accumulation of tailings and transient changes in infiltration rate, decant pond extent and elevation and in head/saturation within the TMF during its life; and the longevity of plastic liners in a TMF scenario.

Conclusions

Extensive research over the past 25 years has demonstrated that the hydraulic performance of clay (CCL and GCL) and geomembrane liners is very different, both in the mechanism through which seepage through the liner occurs and the time dependence of their performance. Published relationships and experimental data allow leakage through GMLs to be calculated and the changes which occur with time as a result of chemical oxidation and degradation to be considered. Consideration of these mechanisms is essential in the meaningful assessment of the hydraulic performance of lined facilities reliant on GMLs. However, difficulties are often encountered in accurately representing GMLs in numerical simulations of hydraulic performance.

A simple approximation is proposed to establish approximate equivalent hydraulic properties in a porous medium for GMLs under varying head conditions and with differing construction controls, allowing incorporation of the performance of GMLs into numerical models. While the suggested approach is an approximation, it is considered appropriate for 'top down' modelling approaches aimed at understanding the overall performance of facilities at a large scale.

The proposed methodology has been applied successfully in completion of a simple and cost-effective comparative assessment of a containment designs for a

TMF, allowing decisions to be undertaken regarding the TMF design requirements at a relatively early stage in the design development.

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