Approach to tailings facility liner configuration selection: A case study

Dan Hughes-Games, P.Eng., P.E.[1*], *Kate* Patterson, P.Eng., P.E.[1], *Len* Murray, P.Eng., P.E.[1], *Cole* Mrak, P.Eng.[1], and Dr. *Kerry* Rowe, OC, P.Eng[2]

[1]Klohn Crippen Berger, Vancouver, BC, Canada
[2]Queens University, Kingston, Ontario, Canada

Abstract. What liner configuration should you use for a tailings facility? Do you need a geosynthetic liner? Should you include overdrains above your liner? This paper presents an approach to answer these questions for a case study tailings facility in a semi-arid environment. The case study project includes a performance criterion that the seepage flux be limited below the impoundment. Four liner configurations were shortlisted, and the efficacy of each arrangement compared with numerical modelling. The configurations are: (1) tailings directly over a liner, (2) tailings on an overdrain system over a liner, (3) tailings on an overdrain system over a blinding layer over a liner, and (4) sealing the foundation with tailings slimes (i.e., no geosynthetic membrane). This paper also presents estimates of the longevity of an HDPE liner system, as this is vital in assessing performance over very long time periods. Seepage and consolidation modelling results indicate that overdrains do not improve the potential to meet the performance criterion and overdrains have a limited post-closure consolidation benefit. All configurations with geosynthetics indicated the liner system would function adequately during the period prior to geosynthetic membrane degradation. The slimes sealing case was shown to not provide an adequate impedance to flow.

1 Introduction

A proposed tailings storage facility (TSF) in a hot and semi-arid climate required evaluation of liner configurations to meet the project's performance criteria which included limiting flux below the impoundment storing fine-grained, potentially acid generating (PAG) tailings. Local regulation requires that tailings facilities be designed using best available technologies to reduce impacts to important aquifer resources. The Global Industry Standard for Tailings Management (GISTM) (ICMM et al., 2020) similarly requires that a tailings facility must achieve 'safe closure', defined as a facility that does not pose long-term material risks to humans or the environment.

Maintaining PAG tailings in a saturated condition is an industry-accepted practice for reducing the potential for oxidation and lining the impoundment is an industry-accepted method of maintaining a pond and limiting seepage to the foundation. Accordingly, the use

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* Corresponding author: dhughesgames@klohn.com

of a liner was proposed as a means to maintain saturation of the PAG tailings and limit seepage flux from the tailings to the foundation groundwater aquifer. A geosynthetic liner was proposed for the project; however, it is acknowledged that while geosynthetic materials are long-lived, they have finite service life.

This paper describes the selection process used to shortlist liner configurations, describes the methods used for estimating the flow through defects in the liner system, and highlights some key technical conclusions based on seepage and consolidation modelling completed to compare efficacy of liner configurations.

2 Proposed Liner Configurations

2.1 Geosynthetic Liner Material Type Selection

Preliminary liner material screening and selection was carried out. Various options were considered including high-density polyethylene (HDPE), linear low-density polyethylene (LLDPE), geosynthetic clay liner (GCL), bituminous geomembrane (BGM), polyvinyl chloride (PVC), bentonite amended soil, and sealing of the foundation with tailings slimes. Following a qualitative evaluation (comparison of operational performance, post-closure performance, constructability, and operability using a ranked scoring system), the project selected HDPE as the preferred liner material.

Slimes sealing using non-PAG cyclone overflow tailings was eliminated as a preferred alternative during the liner material screening process on the basis that it was not expected to achieve adequately low hydraulic conductivity. However, it was included in the subsequent numerical analysis of liner performance to provide comparison to a low-cost, non-synthetic alternative to the HDPE system.

2.2 Liner Configurations

Local regulatory guidance regarding best available technology promotes the use of overdrains in conjunction with a geosynthetic liner. Overdrains consist of a permeable element intended to allow drainage of seepage leachate from above the geosynthetic liner membrane. The intent is to reduce pore water pressures in the tailings, which would lower the hydraulic gradient across the liner and lower the ultimate hydraulic conductivity of the tailings by enhancing consolidation.

Three geosynthetic liner configurations were developed which varied by the inclusion and/or position of overdrains, a fourth configuration includes slimes sealing, as shown in Figure 1:

Configuration 1 – Liner only
Configuration 2 – Overdrains on liner
Configuration 3 – Overdrain on tailings on liner
Configuration 4 – Tailings slimes layer

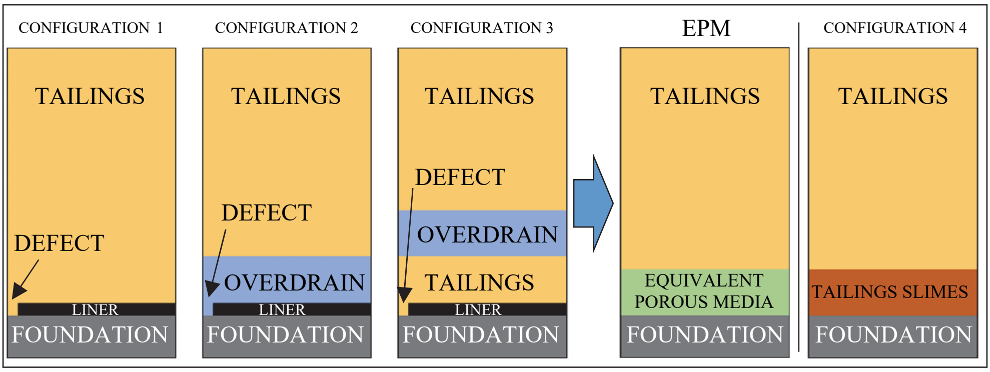

Figure 1. Evaluated Liner Configurations

3 Geosynthetic Liner Longevity

3.1 Literature Review

The project required an understanding of the expected longevity and hydraulic performance of the liner over time to assess the efficacy of the liner configurations. Parameters that influence the longevity of the liner system include (in rough order of relative importance) (USBR 2014, Rowe and Yu 2018; Rowe et al. 2019b; Rowe 2020; Rowe et al. 2020; Zafari et al. 2023; Abdelaal et al. 2023):

1. Material selection (thickness, texture, colour, resin, antioxidant content, other additives)
2. Long-term service temperature
3. Subgrade conditions
4. Quality of installation, including control of wrinkles
5. Temperature variability before cover (with respect to thermal strains)
6. Ultraviolet light exposure before cover
7. Method of cover (hydraulic versus mechanical)
8. Tailings porewater properties

Liner performance depends on retention of key physical properties, especially stress crack resistance, which provides the primary resistance to cracking (Rowe and Yu 2018; Rowe et al. 2019a,b; Rowe 2020). The physical properties degrade as the HDPE polymer structure decomposes, mainly by thermo-oxidation of the polymer chains. Commercial HDPE geomembranes incorporate antioxidants to resist this; however, the antioxidants eventually become deactivated or depleted.

3.2 Expected Geosynthetic Liner Performance

Sources of leakage from a geomembrane liner include defects in manufacturing (relatively rare), defects in seaming, and accidental damage during and after installation. The expected number of defects per hectare is dependent on initial installation quality. The design adopted an assumption of “good” installation quality and an associated average of five point-defects per hectare (two per acre) (USBR 2018).

Climate data from site was used to evaluate the expected performance of the HDPE geomembrane over time. The average ground temperature of the site was estimated from a groundwater monitoring well that recorded average water temperatures of 30°C at 30 m depth, driven mainly by geothermal gradients (i.e., relatively insensitive to climate change).

This is considered representative of the long-term equilibrium temperature of the liner once tailings deposition is complete (after several decades). The relatively warm in-service temperature decreases the expected longevity of the HDPE, even for a product with high-quality, customized additive formulation.

The potential longevity of the liner was calculated from the results of ongoing trials using Arrhenius methods and confidence intervals were given for three stages of liner degradation, as shown in Table 1 (Rowe unpublished but based on Rowe et al. 2020 and Zafari et al. 2023). Each of these stages is associated with a defect configuration, which was then assessed to predict the expected liner performance with time.

Table 1. Liner longevity estimates for a specific high-performance geomembrane, generically denoted MxBTW20, based on five years of testing as reported by Zafari et al. (2023)

Liner Stage	Defect Configuration	Longevity Estimate	
		95% probability of being exceeded (i.e., exceeded 19 times out of 20)	50% probability of being exceeded
L_{100} Stage 100% stress crack resistance	5 × 10 mm diameter perforations per hectare as installed	580 years	900 years
L_{50} Stage 50% representative stress crack resistance	0.22 mm wide cracks, 0.05% of total liner area	790 years	1,300 years
L_0 Stage 0% stress crack resistance	0.22 mm wide cracks, 0.25% of total liner area	1,000 years	1,600 years
L_{dis} Stage Long-term degraded condition	0.22 mm wide cracks, 0.8% of total liner area	1,300 years	3,600 years

The two stages of interest in this paper are the L_{100} stage (the initial in-service performance of the liner before degradation) and the L_{dis} stage (the equilibrium achieved after the final degraded state of the liner is reached).

4 Seepage and Consolidation Modelling Analysis

Seepage and consolidation modelling analysis was undertaken to evaluate the expected degree of saturation and seepage flux to the facility foundation over time. This was evaluated using a series of one-dimensional models using three software programs: TOUGH2 (Berkeley Labs 2020), FSConsol (GWP 2014), and GeoStudio Seep/W (Geoslope 2021). The implementation of each of these is explained in the following sections.

The overall seepage and consolidation model was constructed in TOUGH2, a finite difference program formulated to evaluate multi-phase flow in porous media. The TOUGH2 model was supported by analysis using Seep/W to approximate the average one-dimensional performance of the liner configuration with defects. The consolidation results of TOUGH2 were compared to consolidation estimates using FSConsol as a check.

4.1 Liner Equivalent Porous Media (EPM) Concept

Leakage through defects in an otherwise effectively-impervious geosynthetic membrane liner is an inherently three-dimensional problem. Seepage is assumed to flow downward through the tailings mass and then converge to point defects or linear cracks under saturated or unsaturated hydraulic gradients. A one-dimensional approximation of average liner performance (i.e., effective flux through the liner system) was required in order to execute the TOUGH2 seepage and consolidation model. Liner performance was evaluated using the concept of an Equivalent Porous Media (EPM).

The porewater flow in the tailings was conceptualized in Seep/W by preparing a two-dimensional model to evaluate the flux through a single defect. The defects were assumed to be uniformly spaced and the area of liner between defects was assumed to be impermeable. A second model was then prepared for each case by replacing the liner and defect with a 1 m-thick homogenous material, the eponymous EPM. The saturated hydraulic conductivity of the EPM was varied until the overall flux through the model matched the point defect case. This approach was replicated for the three geosynthetic liner configurations (see Figure 1). The numerical results for circular holes were checked with analytical solutions (Rowe and Fan 2021) and the results for linear defects were checked against the general solution provide by Rowe and Fan (2022).

The typical initial construction point defect for the L_{100} stage was assumed to be equivalent to a circular hole with a radius of 5 mm, based on (Rowe 2012) and (Rowe 2020). For the L_{100} stage, given an average five defects per hectare, each defect has a catchment of approximately 0.2 hectares. The flow to the defect was evaluated as an axis-symmetric two-dimensional model with a width of 25 m and a sector angle of 360°. Linear defects with equivalent leak area were evaluated as sensitivity cases and produced results similar to the circular hole cases. The typical geometry associated with the axis-symmetric L_{100} stage model is on Figure 2.

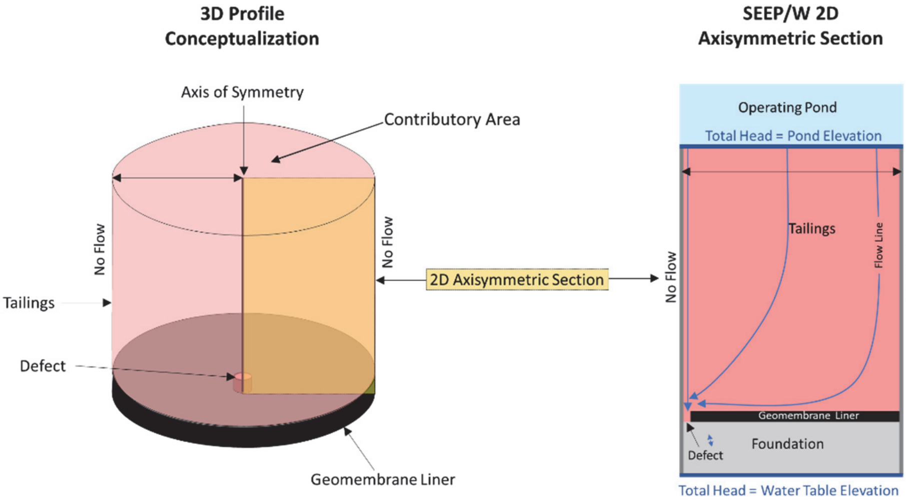

Figure 2. Axis-symmetric EPM Model

For the L_{dis} stage, the liner defects were assumed to be a closely spaced network of cracks. The average crack width was assumed to be 0.22 mm and the average area of the gaps in the liner was assumed to be 0.8% of the total area. The stage was modelled using a two-dimensional planar model of unit thickness, a defect at one lower corner, and a width of 0.0125 m. The associated spacing between parallel cracks is about 2.8 cm. The typical geometry associated with the L_{dis} stage model follows a similar concept as in Figure 1, except the model is two-dimensional (i.e., planar) rather than axis-symmetric.

The Seep/W model geometry represented the contributory tailings mass above the liner, overdrains, if applicable, the liner with defect, and the foundation below the liner. The tailings column height was approximately 60 m, derived from the TSF staging design. The liner/defect area height matched the selected HDPE geomembrane thickness, approximately 2 mm. The overdrain case could also be modelled using the Fan and Rowe (2023) analytical solution.

Table 2 shows the hydraulic conductivity assigned to each material in the model.

Table 2. Hydraulic Conductivity.

Material	Hydraulic Conductivity	
Geosynthetic Liner	Intact liner area assumed to be effectively impervious	
PAG Tailings	Vertical: $K_{sat} = 1\times10^{-6}$ cm/s; Horizontal: $K_{sat} = 5 \times 10^{-6}$ cm/s	
Overdrains	$K_{sat} = 5\times10^{-4}$ cm/s	
Tailings Slimes	$K_{sat} = 5x10^{-6}$ cm/s	
Foundation	Vertical: $K_{sat} = 1\times10^{-4}$ cm/s Horizontal: $K_{sat} = 1 \times 10^{-3}$ cm/s	van Genuchten Parameters: $\alpha = 0.035$ /cm n = 1.298 residual saturation = 0.053

The PAG tailings hydraulic conductivity represents the approximate expected hydraulic conductivity at the base of a fully consolidated column, calculated from Rowe Cell consolidation test results on pluviated tailings. Unsaturated hydraulic conductivity of the foundation was based on site characterization studies. For models with overdrains, the drain layer was assumed to be 1 m thick and was assigned hydraulic conductivity representing relatively clean sand (e.g., cyclone underflow tailings). For Configuration 2 (overdrains on liner) the overdrain properties were also assigned to the defect area. For Configuration 3 (overdrains on tailings on liner), the defect area was assigned the properties of tailings and the layer of tailings between the overdrains and liner was 1 m thick. Tailings slimes were assigned hydraulic conductivity representing typical cyclone overflow tailings.

Boundary conditions for the model consisted of a 3 m pressure head boundary on top of the tailings to represent water cover on the tailings and a 0 m pressure head boundary at the base of the foundation layer representing the underlying aquifer. The model was not sensitive to the distance between the liner and the aquifer – the foundation was arbitrarily assigned a thickness of 1 m. The sides of the model were no-flow boundaries in accordance with the basis of the model.

A long-term closure case was modelled early in the analysis. In that case the top of the model included soil cover representing a dry or phreatic closure cover, and the upper boundary condition was set to the average expected net seepage flux. The analysis showed that the variation in boundary conditions had little effect on the EPM results. The subsequent analysis was simplified to only consider a saturated top boundary representing the operational pond. The effect of a variable climate boundary at the top of the model has implications later in the analysis workflow, as discussed below.

The EPM models were similar to the liner models in total height and configuration, with the lower-most 1 m of the model above the foundation consisting of the EPM material.

4.2 Equivalent Porous Media (EPM) Analysis Results

The EPM hydraulic conductivity for the modelled cases is summarized in Table 2. Key observations from the EPM analysis:

1. Configuration 1 (liner only) has significantly lower L_{100} stage hydraulic conductivity than the other configurations.
2. Configuration 2 (overdrains on liner) had about two orders of magnitude higher hydraulic conductivity in the L_{100} stage than Configuration 1, with about an order of magnitude higher flux.
3. Configuration 3 (overdrains on tailings on liner) had about one order of magnitude higher hydraulic conductivity in the L_{100} stage as Configuration 1, and similar order of magnitude flux.
4. The eventual hydraulic conductivity in the L_{dis} stage for Configurations 1 through 3 is effectively similar and is controlled by the tailings vertical hydraulic conductivity (note, this may not be the same conclusion for tailings with a higher hydraulic conductivity).
5. Configuration 4 (tailings slimes layer) has a hydraulic conductivity that is many orders of magnitude higher than any of the other configurations. The hydraulic conductivity in the L_{dis} stage is about an order of magnitude lower than the degraded liner cases, but has a similar order of magnitude flux

Table 2. EPM Hydraulic Conductivity and Seepage Flux

Liner Configuration	L_{100} Stage		L_{dis} Stage	
	Hydraulic Conductivity	Flux	Hydraulic Conductivity	Flux
Configuration 1 Liner Only	2×10^{-11} cm/s	8×10^{-10} cm/s	3×10^{-5} cm/s	9×10^{-7} cm/s
Configuration 2 Overdrains on liner	3×10^{-9} cm/s	1×10^{-8} cm/s		
Configuration 3 Overdrains on tailings on liner	2×10^{-10} cm/s	5×10^{-10} cm/s		
Configuration 4 Slimes Sealing	5×10^{-6} cm/s	4×10^{-7} cm/s	5×10^{-6} cm/s	4×10^{-7} cm/s

The analysis shows that placing overdrains directly on the liner (Configuration 2) leads to a potentially adverse outcome during the liner service life due to the effect of the drain system allowing seepage to freely flow towards the defect, as compared to the case without overdrains which benefits from the lower horizontal hydraulic conductivity of the tailings. The drainage layer effectively allows downward flow into from the overlying tailings to "shortcut" to the defect. This effect is somewhat mitigated by blinding the liner with a tailings layer (Configuration 3). These general findings are similar to those of Rowe et al. (2017) and Fan and Rowe (2023).

4.3 Tailings Consolidation Modelling

Tailings consolidation and seepage flux modelling was undertaken for staging of the TSF in TOUGH2. Consolidation was evaluated using a proprietary Klohn Crippen Berger Ltd. in-house add-in for TOUGH2 which evaluates consolidation and unsaturated hydraulic conductivity relationships in each model cell at the end of each time-step based on Gibson

(1967). The add-in adjusts the cell height to reflect effective stress versus void ratio relationships, and adjusts the saturated hydraulic conductivity of each cell based on void ratio. The model allows for saturated and unsaturated conditions. Tailings soil-water characteristic curves (suction versus volumetric water content and hydraulic conductivity versus suction) were scaled to saturated hydraulic conductivity for each cell.

The model was run on a 12-hour time step from the start of mining until approximately 500 years after closure. During the operational period, tailings were added to the top of the one-dimensional column on a monthly basis based on the TSF staging plan. The upper boundary condition consisted of 3 m depth of water representing the operational water pond. The tailings were capped with closure cover material at the end of operations, and the upper boundary was changed to reflect simulated climate data derived from a 1,000-year stochastic climate model. The model approximated net infiltration and evaporation consistent with other closure analysis.

The model concluded that for the L_{100} stage liner EPMs, Configuration 1 (liner only) and Configuration 3 (overdrain on tailings on liner) maintain basal flux within acceptable limits and the tailings are expected to remain saturated. Configuration 2 (overdrains on liner) and Configuration 4 (tailings slimes layer) have basal flux that is too high in relation to the expected water balance constraints and will not maintain saturation in absence of a surface water pond (i.e., the period after operations but before the liner degrades).

The model results show that for the L_{dis} stage liner EPMs, flux through the liner will increase until it is limited by the expected net infiltration at the ground surface, which is mainly a function of surface evaporation in the arid climate. As a consequence, the upper portions of the tailings could potentially desaturate to a degree that would allow oxidation of the PAG tailings in the long term. Tailings at depth would likely remain saturated.

5 Limitations

One of the inherent limitations of this approach is the use of one-dimensional columns to evaluate overall seepage flux. The analysis necessarily requires an assumption of no horizontal flow; however, variations in the height of adjacent tailings columns and the potential for internal heterogeneity need to be considered, and two-dimensional or three-dimensional models may be required for detailed characterization. However, as shown by Rowe et al. (2021) the critical region controlling the flow is within about five hole-diameters of the defect.

The EPM formulation used in this study was simplified in a few ways that influence the results; however, sensitivity analysis showed that the overall trends were correct at an order of magnitude level. Simplifying assumptions in the EPM analysis include the use of a single hydraulic conductivity for the full height of the PAG tailings column, and the use of a constant pressure head boundary at the top of the model in the L_{dis} stage, when the facility would have closure cover material exposed to a variable climate boundary with low net infiltration.

6 Conclusions

The analysis presented herein is the first step to selecting a liner configuration and ultimate design. The conclusions of the analysis were adequate to understand the performance and limitations of the specific liner configurations presented and advanced the understanding of overall facility performance expectations.

The main conclusion of this initial analysis is that the concept of including overdrains directly on a liner system does not add value for the specific scenario, performance requirements, and tailings properties of the project. Since the objective is to limit flux to the foundation below the liner system, blinding any potential leaks in the liner is advantageous. Potential mitigations could include the use of composite liner systems that have the potential to blind-off leakage through point defects; however, it should be noted that tailings appear to be quite effective in this regard.

The prediction of eventual desaturation of a portion of the tailings in the long term (i.e., L_{dis} stage) necessitates evaluation of alternative mitigations in order to maintain tailings saturation; however, the timing of liner degradation places the onset of potential impacts hundreds or thousands of years post-closure.

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