To line or not to line - the effect of geometry on seepage rates from tailings storage facilities

John Waterhouse[1], Robin Friday[2]

[1] Golder Associates, 441 Vincent Street West, Leederville, W A 6007, Australia
[2] Golder Associates, 25 Burwood Road, Hawthorn, Victoria 3122, Australia

Abstract: Seepage from conventional tailings storage facilities (TSFs) is inevitable. This paper discusses the control which geometric and hydraulic factors may exert on long term seepage.

For a large TSF overlying a relatively shallow and poorly transmissive groundwater flow system, the rate of downward seepage may initially be high. However, when the zone beneath the TSF has saturated, the longer term seepage rate may be limited by the capacity of the groundwater system to transmit seepage laterally. In this situation, an ordinary liner may only slightly reduce long term rates of seepage. In an extreme case, only a near-perfect synthetic liner may control the seepage rate more effectively than the inherent properties of the groundwater flow system.

For a smaller TSF with a deeper and more transmissive groundwater system, the long term seepage rate may not be limited by the system characteristics so much as by the hydraulic conductivities of the tailings and the unsaturated materials immediately under the TSF. The volume beneath the TSF may not saturate and seepage rates will not be limited by the capacity of the groundwater system to transmit seepage laterally. In these situations, liners may be more effective if control of seepage is required.

1 INTRODUCTION

Tailings storage facilities (TSFs) are used for the permanent disposal of wastes from the treatment of a variety of ores, typically utilising a slurry deposition method. Evaporation ponds for disposal of waste water such as mine dewatering discharges and tailings liquours behave in a similar manner to TSFs and are implicitly included in this discussion. Seepage from other tailings disposal methods such as dry stacking and paste technology are not considered in this paper.

Unless elaborate methods, such as double liner systems, are used, some seepage from a TSF is an inevitable consequence of the deposition of a slurry within bounding embankments.

The purpose of this paper is to explore some of the controls on seepage rates which become significant when large storages overlie groundwater flow systems of limited thickness and low hydraulic conductivity.

The paper is written from the perspective of the Western Australian mining environment, where environmental management is evolving in the context of numerous mines in remote, arid locations. Whilst a detailed description of the hydrogeology of Western Australia is beyond the scope of this paper, a short description of the most common hydrogeological setting for the facilities which are discussed is appropriate.

Typical Western Australian base metal or gold mining and processing projects are located in a large area of Archaean rocks with generally low topographic relief with a generally similar geological profile. This profile comprises thin soils or alluvial material underlain by a lateritic profile of variably iron-cemented, extremely weathered rock of various lithologies. The weathered rocks grade into fresh rock at depths that vary from zero (fresh rock at surface) to, more commonly, several tens of metres. Whilst at some localities the rocks themselves are permeable enough to form heterogeneous aquifers, it is more typical for hydraulic conductivities, particularly in the extremely weathered zone and the fresh rock, to be so low that the materials below the water table can barely yield water to wells. Often, the most permeable material is found in the transitional weathering zone immediately above fresh rock (Morgan, 1993)

The depth to the water table is commonly in the approximate range 10 m to 40 m, although of course this depth varies according to the local topographic relief. If, as is common, the main transmissivity is in and near the base of the weathered zone, the thickness of the aquifer may be small and even when the saturated thickness is increased by seepage, the transmissivity may not increase significantly.

Groundwater quality in the weathered to fresh rocks is variable, ranging from less than 1 000 mg/L total dissolved solids to 5 000 – 10 000 mg/L (Allen, 1996) or more in places.

The climate in most of this area is semi-arid, with annual rainfall typically less than 300 mm and annual pan evaporation in excess of 2 000 mm. Soils are usually low in moisture content, clayey and with typically negative pore pressures.

Larger mining and processing projects have potential to be active for periods of 20 – 30 years.

2 SEEPAGE MECHANISMS

We start with a consideration of the mechanisms by which seepage develops progressively beneath a TSF. There are three stages in the development of seepage flow from a TSF:

1. Initial seepage as the first layer of tailings is deposited, when the decant pond does not have an underlying layer of tailings.
2. Seepage through a progressively thickening tailings deposit.
3. Continued seepage, at declining rates, by drainage of the tailings deposit after cessation of operations.

In parallel, but not necessarily corresponding stage by stage, there are five possible stages in the evolution of the saturated-unsaturated profile and hydraulic gradients beneath the TSF:

1. Initial downward movement of a saturation front, mostly directly beneath the decant pond.

2. Mounding of the underlying water table in response to an increasing flux through the unsaturated zone.
3. Coalescing of the downward moving saturated seepage front with the upward moving water table (unless the water table aquifer has high transmissivity).
4. Development of an overall gradient for lateral flow away from the TSF, with fully saturated conditions beneath the decant, and a slowly rising water table.
5. Progressive decay of the groundwater mound after the cessation of operations.

The profile evolution may not always develop exactly in this way, for example, if horizontal layers of low vertical hydraulic conductivity cause the development of a shallow, perched system, in turn possibly preventing full saturation of the profile. It is important to recognise that the geological systems which we are considering are often heterogeneous at the scale of a TSF and also variably anisotropic.

The downward seepage through the unsaturated zone is likely to be as a saturated front if there is no effective liner and the seepage source is relatively localised, as is anticipated when a tailings decant pond is formed. Otherwise the downward seepage may occur as an unsaturated wetting front.

It is important to the understanding of this paper to recognise the potential for high rates of initial seepage due to a combination of void filling, the large area over which saturated tailings may drain and the possibility of the hydraulic gradient exceeding one as a consequence of soil suction. The factor which opposes the high seepage tendency is the relationship between the degree of saturation and the vertical hydraulic conductivity which impedes the downward flux. Simple calculations of downward seepage rates using Darcy's Law and saturated hydraulic conductivity values obtained by field testing will tend to predict high rates of seepage.

3 LINER PROPERTIES

Liners are perceived by some as providing a control over seepage rates by "sealing" the base of facilities such as TSFs or evaporation ponds. Whilst the hydraulic conductivity of a liner is by definition expected to be lower than that of the material above or beneath it, the long term effect of the liner will depend upon the amount of hydraulic resistance that it imparts to the flow system as a whole.

The hydraulic conductivity of liners varies over many orders of magnitude. Our experience in Australia suggests that in practice it is difficult to achieve vertical hydraulic conductivities lower than 10^{-8} to 10^{-9} m/s for compacted clay. Given practical difficulties in maintaining appropriate moisture content during construction and before coverage with tailings is complete, these values may be optimistically low.

Synthetic membranes such as high density polyethylene (HDPE) may, under ideal conditions, have hydraulic conductivities as low as 2×10^{-15} m/s, (Giroud and Bonaparte, 1989). However, even minor defects increase the effective hydraulic conductivity by several orders of magnitude. The effective resistance to vertical seepage of various liners is compared in Table 1.

The effective resistance of the two HDPE liners was calculated using the HELP3 computer program produced by Schroeder et al, (1994). This program is typically used for hydrologic evaluation of landfill performance and takes account of the typical defects which have been observed in manufacturing and placement of synthetic membranes. The three main aspects affecting synthetic membrane liner performance are:

- Manufacturing defects, usually small size holes (pinholes)
- Larger holes left during installation due to damage, incomplete coverage or faulty welding
- Placement care affecting the uniformity of contact between the membrane and adjacent low permeability soil

For the two HDPE installation standards we assumed:

	Poor	**Good**
Pinholes/hectare	2	1
Installation holes/hectare	10	2
Placement quality	Poor	Good

Table 1 Comparison of liner resistances

Liner type	**Effective resistance b/K (s)**	**Leakage with water head 10 m above base (m^3/day/km^2)**
Compacted clay K = 10^{-8} m/s, 200 mm thick	2 x 10^7	43000
Compacted clay K = 10^{-9} m/s, 600 mm thick	6 x 10^8	1400
HDPE – poor installation adjacent to material with K = 10^{-8} m/s	1.4 x 10^9	620
HDPE – good installation adjacent to material with K = 10^{-9} m/s	1.4 x 10^{11}	6
Tailings K = 10^{-8} m/s, 10 m thick (saturated)	1 x 10^9	860
Compacted clay K = 10^{-9} m/s, 600 mm thick under 10 m of tailings	1.6 x 10^9	540
HDPE – poor installation under 10 m tailings	2.4 x 10^9	360
HDPE – good installation under 10 m tailings	1.4 x 10^{11}	6

b = liner thickness

K = effective vertical hydraulic conductivity of liner

HDPE = High density polyethylene

4 EFFECTS OF DIMENSIONS AND LINER PROPERTIES

The important difference between seepage from large and small TSFs is that the long term seepage from a large storage, that is greater than about 1-2 km^2 has greater potential to be constrained by the geometry and properties of the groundwater flow system. This is due to the potential for a large discrepancy between the relatively small cross-sectional area for lateral flow under a low hydraulic gradient and the relatively large area for downwards seepage under a hydraulic gradient which may exceed one.

An estimate of the radial seepage capacity of the aquifer beneath the TSF may be made to illustrate the focus of this paper using the Thiem steady-state formula.

$$Q = 2 \pi T s / \ln(R/r)$$

where:

Q = steady radial flow
T = transmissivity
s = groundwater mound height
r = radius to which the mound is applied
R = radius of fixed head boundary

Table 2 shows some results of lateral flow calculations for TSFs of different radii for two different aquifer transmissivities assuming R = 3.5 km and s = 20 m.

Table 2 Aquifer radial flow estimates

TSF area (km^2)	TSF radius (km)	Radial flow rate (m^3/day)	
		Transmissivity 1 m^2/day	Transmissivity 10 m^2/day
1	0.56	69	690
2	0.80	85	850
5	1.26	120	1200
10	1.78	190	1900

Comparing the results in Tables 1 and 2 it can be seen that for an aquifer transmissivity of 1 m^2/day the aquifer has less lateral flow capacity than the liner for all cases except the HDPE with good installation characteristics. This transmissivity value has been adopted from an actual case study in which the hydraulic conductivity values calculated from field testing of the weathered zone aquifer were in the range 10^{-6} to 10^{-7} m/s for an aquifer thickness of about 25 to 30 m. If a good quality of liner could be installed in practice, it would be intended that most of the seepage water would be collected in a toe drain or some form of blanket drain above the liner and that only a small amount would seep down to groundwater.

No large tailings storage facility in Western Australia has ever been lined effectively and drained in this way to our knowledge.

For all the other liner types it can be expected that seepage will cause the groundwater to mound by up to 20 m or more above the pre-operational water table. In this situation, excess water (that which cannot be transmitted by the aquifer) may either appear as seepage around the toe of the TSF or be collected by sub-surface drains around the toe of the TSF. Seepage around the toe of the TSF is environmentally undesirable and can lead to deposition of salts and water-logging of plant roots, causing conspicuous death of adjacent natural vegetation.

For an aquifer with transmissivity of approximately 10 m^2/day (or greater) the analysis shows that the seepage outcome can be influenced by different types of liner beneath the tailings. This is because the liner will exert the main control over the combined system of downward seepage and lateral flow in the aquifer. As the tailings deposit accumulates and consolidates, further resistance to seepage will develop.

Based on the results in Tables 1 and 2, Figure 1 compares the resistance to flow through the liner and through the aquifer for different TSF areas. The resistance is expressed as driving head divided by flow. For the liner this is equal to $H/Q = b/KA$ where H is the head of water over the liner and A is the vertical leakage area. For the aquifer the resistance to steady flow is estimated as $s/Q = \ln(R/r)/2\pi T$. The medium HDPE liner has $b/K = 1.4 \times 10^{10}$ s.

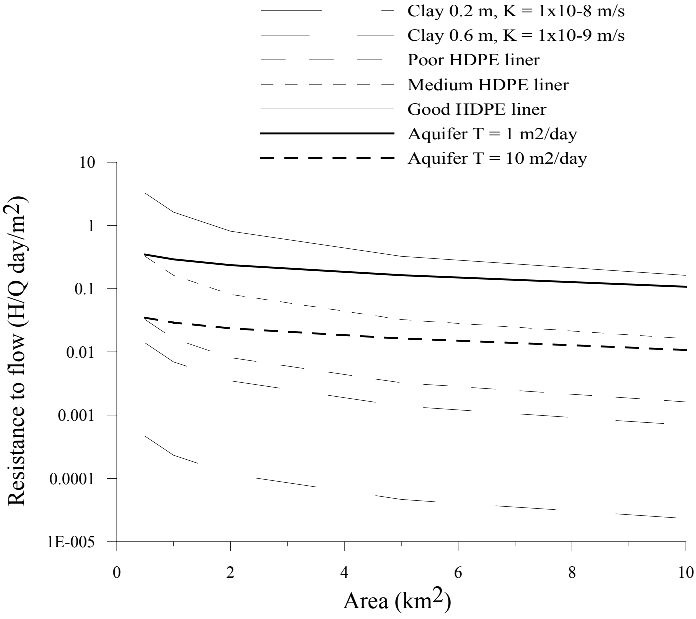

Figure 1 Resistance to seepage for different liners and TSF areas

5 MODELLING

We have carried out transient flow modelling for several cases including tailings storages and evaporation ponds. For this work we have used the computer program Seep/w. Figures 2 and 3 show results from an axisymmetric model for the case of an evaporation pond 980 m radius (3 km^2 area) with a poor HDPE liner. The geology was assumed to be uniform across the site and typical of the Western Australian area of interest, with 1 m of alluvial soil over 9 m of ferricrete over 26 m of extremely weathered bedrock. The liner was modelled using 0.5 m thick finite elements with a vertical hydraulic conductivity selected to match the resistance listed for this case in Table 1.

The model extends to 5 km radius where the groundwater head was fixed at RL –20 m. The initial condition for the model included surface infiltration at a low rate of 0.025 mm/year which raised the groundwater level under the centre of the pond to RL –19 m.

The depth of water in the pond was raised linearly with time from 0 to 1 m over two years, held for 28 years and then reduced linearly with time from 1 to 0 m over two years. The infiltration rate was then reduced to the original value over the whole model area.

Figure 2 shows the water table rising due to seepage from the pond. Figure 3 shows the water table subsiding after the pond is emptied.

Figure 4 shows the calculated cumulative flow of water from the evaporation pond for four different cases:

- No liner
- Clay liner 0.6 m thick with hydraulic conductivity 1 x 10^{-9} m/s
- Poor HDPE liner as used in Figures 2 and 3
- Medium HDPE liner

With the medium liner there was a rise of only 2 m in the water table beneath the centre of the pond. As the water table remained well below the liner, seepage was controlled by the liner. In the other three cases the water table mounded up to the liner within about 1 to 15 years and the aquifer had a significant effect on the total seepage from the pond. The results in Figure 4 are consistent with those expected from the general study leading to Figure 1.

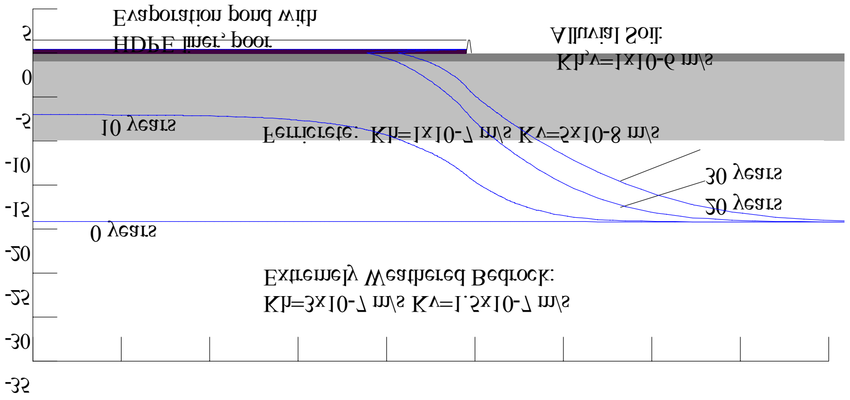

Figure 2 Water tables at 0, 10, 20 and 30 years after start of filling pond

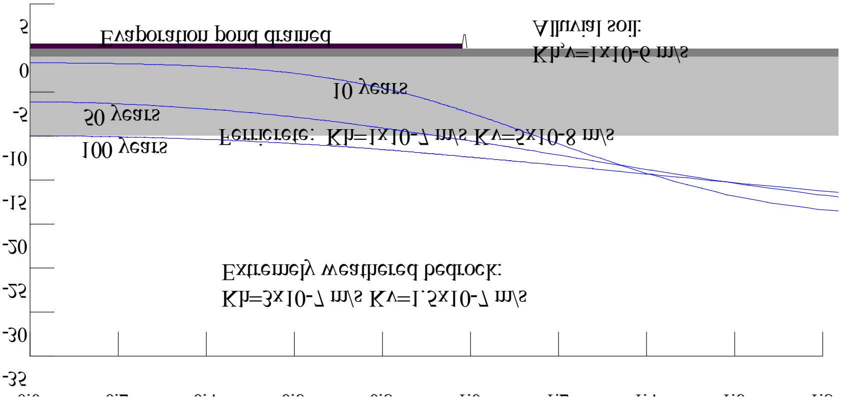

Figure 3 Water tables at 10, 50 and 100 years after draining pond

For the no-liner case the initial seepage rate was limited to no more than 7000 m^3/day, taking account of the water supply to the pond.

Modelling of tailings storages is similar to evaporation ponds but slightly more complicated as layers of tailings must be progressively added to the model and, depending on the aquifer and the liner used (if any) the tailings themselves can influence the seepage results.

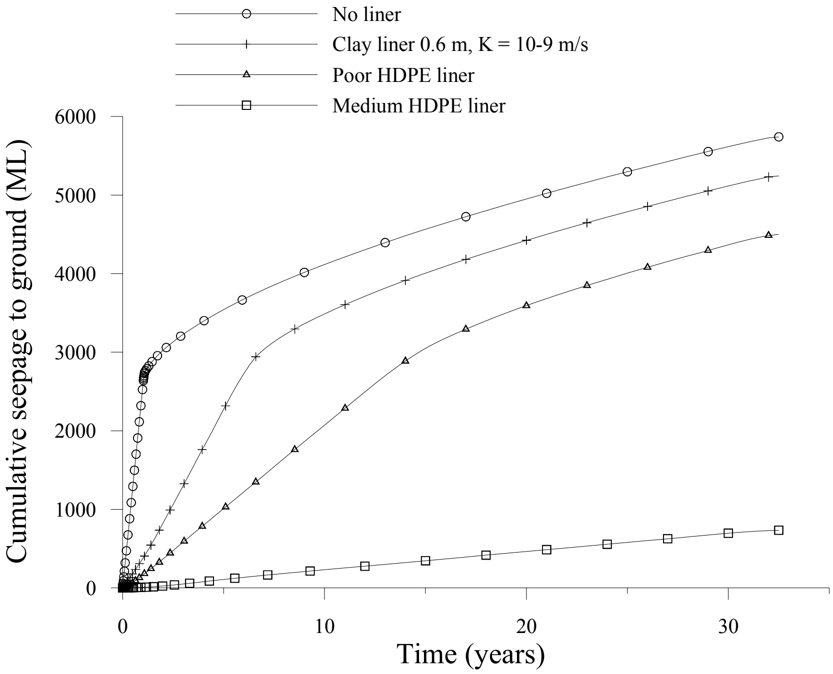

Figure 4 Calculated seepage from evaporation pond

6 DISCUSSION

The analyses and a consideration of the results of modelling various seepage cases show that the effectiveness of liners to control seepage depends on more than the hydraulic conductivity of the liner itself.

This outcome demonstrates a need to assess seepage in the context of the overall groundwater flow system within which the seepage will migrate laterally after it has passed through the base of the TSF or evaporation pond. In the case of aquifer systems that are shallow and thin relative to the area of the TSF, the geometry and properties of the groundwater flow system may exert considerable resistance to lateral flow. This resistance may be greater than most liners would provide to limit vertical seepage.

For most TSF situations, recognition of the nature of seepage control is an important aspect of the design and regulatory approvals process. For example, there is little benefit in spending large sums of money lining a TSF if the liner will not significantly change the long term rate of seepage from the facility. Similarly, there is little benefit to a regulator in requiring a sophisticated liner unless it will be more effective than the natural groundwater flow system.

A related issue is the long term stability and rehabilitation of the area of the facility. For a tailings facility, seepage greatly assists the process of consolidation of the material which has been deposited. Whilst there may appear simplistically to be advantages in preventing seepage for environmental reasons, a poorly consolidated tailings deposit may be more difficult to manage in the long term, since reshaping and revegetation may be difficult and the geotechnical stability may be compromised.

In turn, this emphasises the need for good hydrogeological understanding to be developed early in the investigation of any new site which may be used for tailings deposition or for evaporation ponds.

ACKNOWLEDGEMENTS

The authors thank their Golder Associates colleagues, particularly Mr David Williams and Dr Stephanie Watson, for many useful and stimulating discussions on numerous seepage analysis studies in recent years.

REFERENCES

Allen A.D., 1996. *The Hydrogeology of the Northeastern Goldfields, Western Australia*. Western Australia, Geological Survey, Record 1996/4.

Morgan K.H., 1993. Dewatering open pit mines, Yilgarn Craton, Western Australia. In Robertson I. et al (ed) *Proc. International Mining Geology Conf.,* 285-295.

Giroud J.P.& Bonaparte R. 1989. Leakage through liners constructed with geomembrane liners – parts I and II and technical note. *Geotextiles and Geomembranes* 8(1), 27-67, 8(2), 71-111, 8(4), 337-340.

Schroeder J.R., Dozier T.S., Zappi P.A., McEnroe B.M., Sjostrom J.W., Peyton R.L. 1994., *The hydrologic evaluation of landfill performance (HELP) model*, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS

Stosować drenaż czy nie – wpływ czynników geometrycznych i hydraulicznych na stopień przesączania ze zbiorników flotacyjnych

John Waterhouse, Robin Friday

Streszczenie: Przesączanie z tradycyjnych zbiorników flotacyjnych (TSF) jest nieuniknione. W artykule dyskutuje się jakie czynniki geometryczne i hydrauliczne mogą wpływać na długotrwałe przesączanie. Dla zbiorników poflotacyjnych położonych w stosunkowo płytkim i słabo przepuszczalnym środowisku wód podziemnych stopień pionowego przesączania może być początkowo wysoki. Jednakże, po nasyceniu strefy poniżej TSF, dalsze przesączanie może zostać ograniczone przez zdolność systemu wód podziemnych do przewodzenia poziomego. W takiej sytuacji, wykonany system drenażu może jedynie nieznacznie ograniczyć długookresowy stopień przesączania. W przypadkach ekstremalnych, tylko prawie idealnie wykonany system sztucznego drenażu może kontrolować wielkość przesączania.