Closed-form prediction of leakage through HDPE liner defects underlying tailings dams

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CLOSED-FORM PREDICTION OF LEAKAGE THROUGH HDPE LINER DEFECTS UNDERLYING TAILINGS DAMS

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ABSTRACT

Tailings storage facilities require effective barrier systems to prevent environmental contamination from mining waste materials. Prediction of leakage through liner defects/holes is essential to assessing the effectiveness and equivalence of liner systems. This paper discusses the simulation of flows through geomembrane defects through finite difference analysis. Based on these results, a closed-form solution for leakage rate prediction is proposed, taking cognisance of the effects of anisotropic tailings and varying foundation permeabilities. The proposed solution shows good agreement with work done by Fan and Rowe (2022) and negates the need for complex and time-consuming finite difference analyses or laboratory testing.

Keywords: Tailings dams, HDPE geomembrane, leakage prediction, anisotropic flow, finite difference modelling

1. INTRODUCTION

Lining of tailings storage facilities (TSF) is a regulatory requirement implemented to minimise environmental exposure to potentially hazardous waste materials generated by mining activities. The calculation of expected flows through defects/holes in these liners is a means of assessing the effectiveness of the liner system and can be a complex procedure. Numerous scenarios involving different TSF development stages as well as variability in tailings and foundation permeability must be considered.

The literature available on the assessment of leakage through a geomembrane (GM) is mostly applicable to cases where the liner is overlain by municipal solid waste (MSW) and is not entirely relevant to the conditions encountered in a TSF. This is mainly due to three reasons:

- Tailings is saturated and impermeable, the latter causing a localised head loss within the tailings atop a defect, effectively reducing flow rate (Brachman et al., 2017),
- Hydraulic heads acting on the GM are typically much larger, possibly in excess of 100m, compared to a landfill site,
- Hydraulically deposited tailings often exhibit highly anisotropic flow characteristics which are not captured by methods applicable to landfill liners.

Specific literature on assessing leakage through GMs overlain by tailings is scarce as the application of GMs in the context of tailings dams was still a recent development at the time of writing. However, Fan and Rowe (2021, 2022) made significant contributions towards this topic. Fan and Rowe (2022) studied seepage through a hole in a GM overlain by saturated tailings, atop a well-drained subgrade. Their research involved the derivation of an equation to predict leakage through a GM based on experimental and numerical modelling. The works conducted by Fan and Rowe were based on scenarios where:

- Tailings above the HDPE liner is unlayered, and therefore homogenous and isotropic.

- The permeability of the material underlying the HDPE liner was at least three orders of magnitude greater than the overlying tailings, thereby allowing for relatively free draining conditions below the liner.

The equations proposed by Fan and Rowe (2022), showed good agreement with experimental data presenting errors less than 10% and provided flows much smaller than general landfill leakage scenarios (e.g. Bonaparte et al. 1989 and Giroud et al. 1997) as would be expected.

Table 1 summarises the equations used to estimate seepage occurring through a geomembrane defect as per Fan and Rowe (2022).

Table 1. Equations for the calculation of seepage through a geomembrane defect overlain with saturated tailings by Fan and Rowe (2022).

5mm < Hole radius < 25mm	**25mm < hole radius < 250mm**
1) $Q = 59.89k_1Ht^{0.295}r^{0.097\ln t+1.831}$	2) $Q = 7.35k_1Ht^{0.062}r^{0.034\ln t+1.256}$

Where:
Q = flow (m^3/s)
k_1 = permeability of the tailings (m/s)
H = hydraulic head (m)
r = radius of the hole within the HDPE liner (m)
t = thickness of the liner (m)

Whilst showing promising results, the Fan and Rowe (2022) proposed equations are not applicable to a case where the hydraulically deposited tailings exhibit anisotropic flow properties, or where the material underlying the liner is of similar or lower permeability to the overlying tailings.

The current work was conducted with the aim of providing a means of predicting seepage through holes in GM liner systems underlying a TSF comprising anisotropic tailings and overlying relatively low-permeability material.

2. VALIDATION OF ANALYSIS PROCEDURE

2.1 Methodology

Various 3D Finite Difference Models (FDMs) were setup assuming conditions within the limitations of the Fan and Rowe (2022) work, each with varying defect/hole diameters. A frequency and size distribution of holes in a GM was proposed by Giroud (2016). Giroud found that strict quality control programs typically result in approximately five holes per Hectare ranging between radii of 0.8mm and 1.8mm, and hole sizes were accordingly modelled within this range. Isotropic fluid flow models were assigned to the layers on either side of the GM with the permeability of the material underlying the GM at least three orders of magnitude greater than the material above. The GM was modelled as an impermeable interface with no thickness.

This set of simulations was conducted with the aim of verifying accuracy of the finite difference simulation adopted for the current work through comparison with the Fan and Rowe work. Figure 1 shows the FDM model developed for analysis.

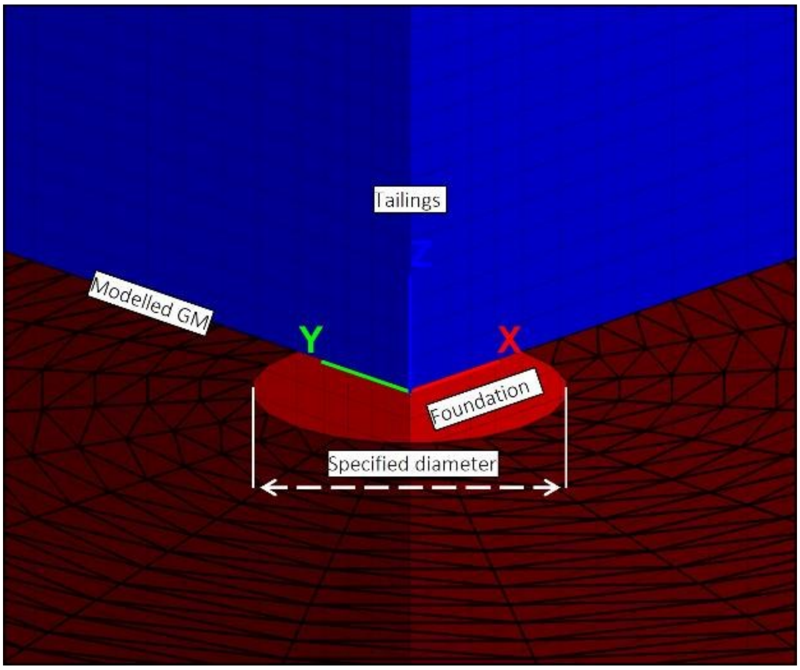

Figure 1. Finite Difference Model of a liner with a 20mm diameter hole

3. CONSIDERATION OF ANISOTROPIC TAILINGS AND LOW-PERMEABILITY FOUNDATION MATERIAL

With the proposed analysis procedure validated, the goal was to simulate the flow through a hole in an HDPE liner overlain by anisotropic tailings and underlain by a low-permeability material. Through interrogation of the simulation results, a closed-form solution to calculating flow under these assumptions could be developed. This closed-form solution would negate the need for complex and time-consuming finite difference analyses.

The validation work illustrated that leakage rates modelled through FDM are directly proportional to the defect radius (r) as well as the hydraulic head (H) and permeability ($K_{tailings}$) of the material atop the GM. A normalised flow parameter could thus be derived, referred to as Q* where $Q^* = \frac{Q}{H \cdot K_{tailings} \cdot r}$.

The remaining non-linear contributors to liner leakage are the anisotropy ratio of the tailings and the ratio between the permeabilities of the materials on either side of the GM, henceforth referred to as the permeability ratio. The various modelled scenarios were processed to determine the individual effect of anisotropy ratio and permeability ratio, respectively, on Q*. The effects of permeability ratio and anisotropy are considered separately in Sections 3.1 and 3.2 respectively.

The variables in the table below were varied within the listed ranges to produce a distribution of flows, allowing for evaluation of the relationships between variables.

Table 2. Variable ranges considered in FDM modelling of leakage through GM defects

Ranges	**Lower bound**	**Upper bound**
Foundation permeability (m/s)	$1.0\text{x}10^{-10}$	$1.0\text{x}10^{-05}$
Tailings permeability (m/s)	$1.0\text{x}10^{-09}$	$1.0\text{x}10^{-06}$
Anisotropy of tailings (k_z/k_x)	0.1	1
Hole radius(mm)	0.8	1.8
Pressure Head (m)	10	100

3.1 The effect of permeability ratio on liner leakage rates

For this assessment, the permeability of the tailings was kept constant at a value of $1\text{x}10^{-8}$m/s, whilst the permeability of the foundation material, and therefore the permeability ratio, was varied. A 100m hydraulic head was applied to all cases. GM defect/hole radii were varied between 0.8, 1.0, 1.3 and 1.8mm.

Anisotropy of the tailings was not varied and will be considered in the following section.

Figure 3 is a chart of the resulting leakage rates. The scatter in the data is due to the variation in hole radius and permeability of the foundation.

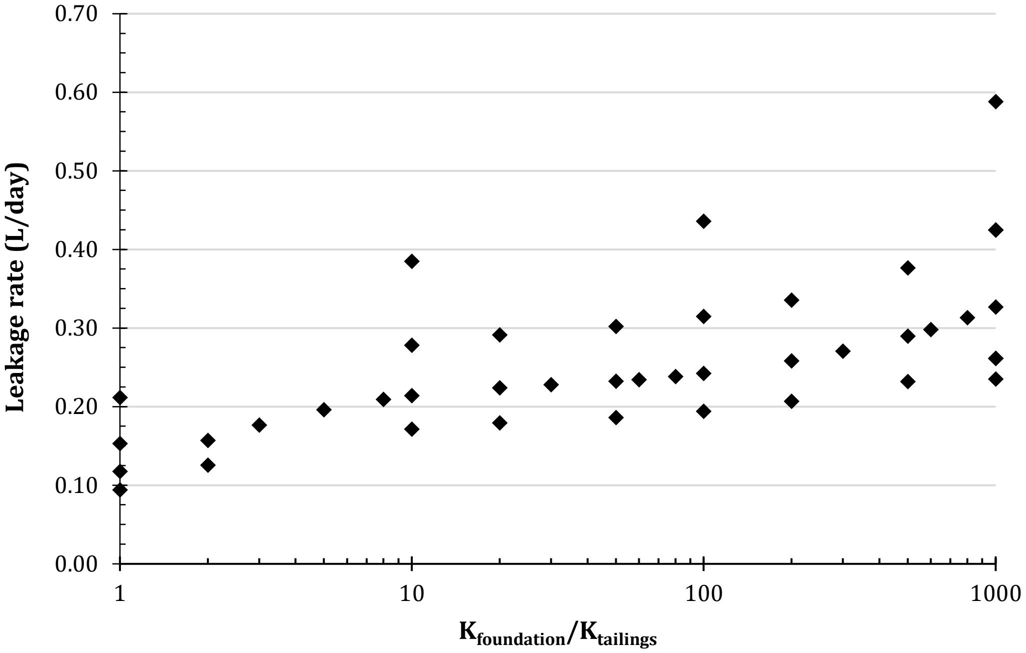

Figure 2. Leakage rate versus permeability ratio

Figure 4 is a normalised version of the modelled leakage rates (Q*) and bares a single relationship between the two variables. It is evident that an increase in foundation permeability results in an increase in leakage rate.

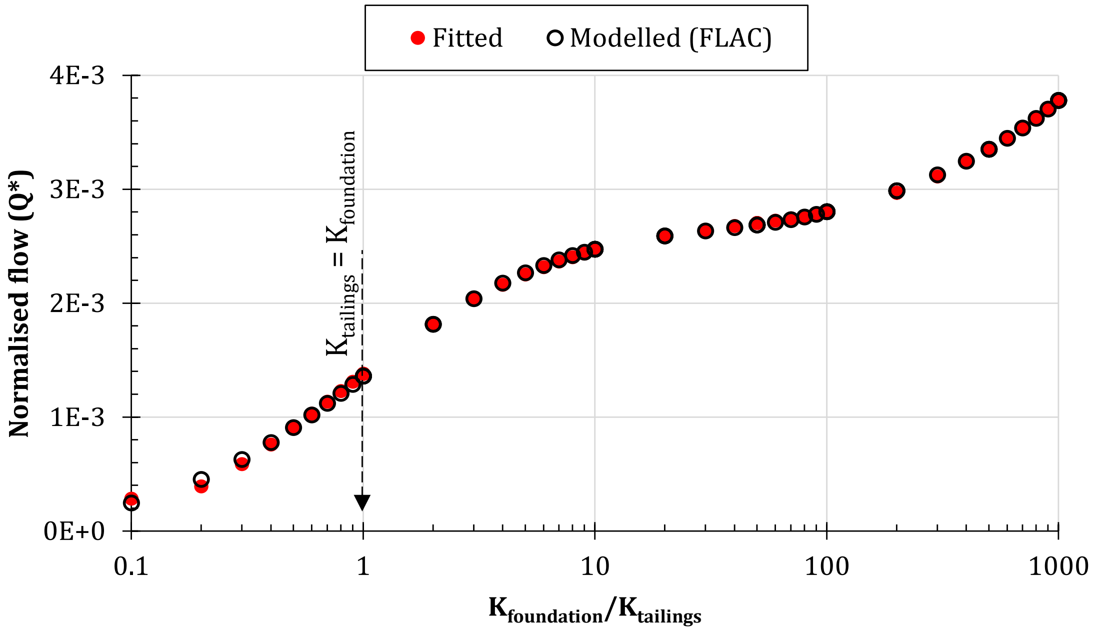

Figure 3. Normalised leakage rate versus permeability ratio

Therefore, through the relationship derived in Figure 4, a normalised **isotropic** leakage rate (Q*) can be estimated based on the permeability ratio. The normalised leakage rate can then be multiplied by H (m), $K_{tailings}$ (m/s) and r (mm) to obtain a leakage rate in m^3/s.

The polynomial fitted to the modelled data is provided below with coefficient values in Table 3.

$$Q^* = ax^5 + bx^4 + cx^3 + dx^2 + ex + f$$

Table 3. Coefficients of the polynomial to calculate isotropic Q*

a	b	c	d	e	f	x
-2.989×10^{-5}	2.4550×10^{-4}	-4.744×10^{-4}	-2.533×10^{-4}	1.698×10^{-3}	1.436×10^{-3}	$\log\left(\frac{K_f}{K_t}\right)^n$

3.2 The effect of anisotropy on liner leakage rates

Hydraulic head was set as 100m, foundation permeability at 1×10^{-5} m/s and horizontal permeability of the tailings at 1×10^{-8} m/s for this set of analyses, whist hole radii and the vertical tailings permeability and therefore anisotropy were varied. Figure 5 shows the modelled leakage rate as a function of anisotropy.

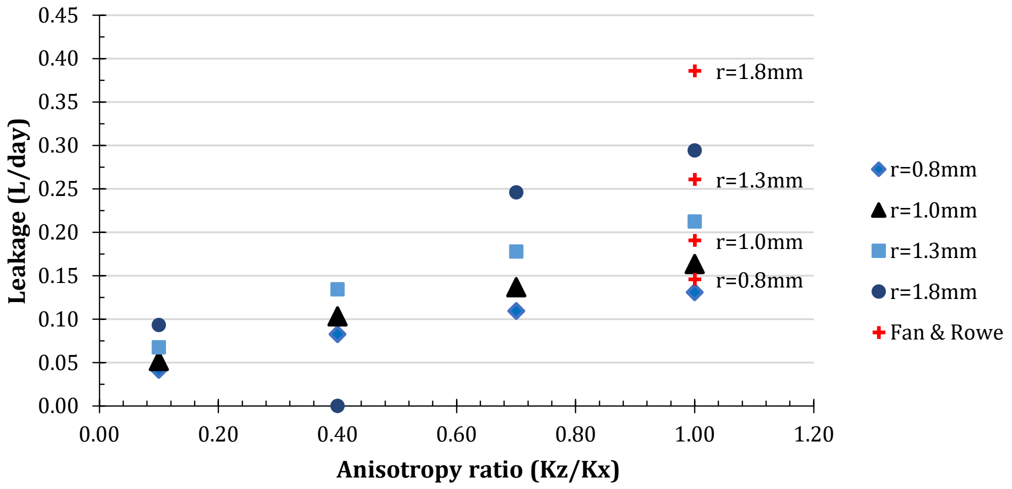

Figure 4. Leakage rates modelled with FLAC plotted versus anisotropy ratio.

Once again, the effect of anisotropy on leakage through a GM was captured through normalisation of flow with hydraulic head, hole radius and tailings permeability (Figure 6). This allowed for determination of the expected reduction in liner leakage brought on by the degree of anisotropy in tailings (Figure 7).

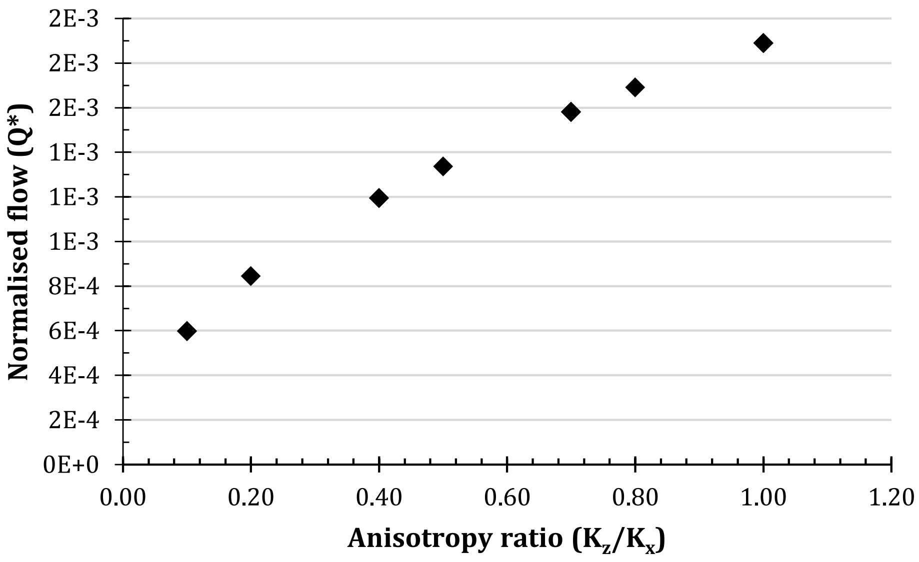

Figure 5 . Normalised liner leakage versus anisotropy ratio

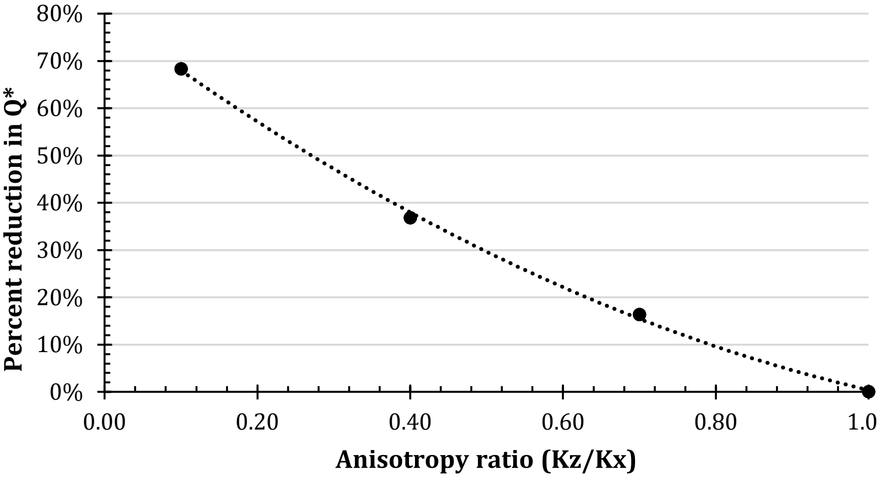

Figure 6. Percentage reduction in the normalised liner leakage due to anisotropy

Figure 7 provides the percentage reduction in normalised flow brought on by the effect of anisotropy. A polynomial fitted to the dataset is:

$$\%\ Reduction\ in\ Q^* = 0.409\frac{{K_z}^2}{K_x} - 1.189\frac{K_z}{K_x} + 0.785$$

Hence, for the case where leakage is estimated through a hole with a given permeability and anisotropy ratio, one would start at Figure 4. A normalised, isotropic leakage rate should be estimated from the permeability ratio, thereafter the normalised isotropic leakage rate should be proportionally adjusted according to the anisotropy ratio (Figure 7). The newly adjusted normalised leakage rate can then finally be converted to m^3/s through multiplication with the corresponding H (m), $K_{tailings}$ (m/s) and r (mm) values.

4. VERIFICATION OF THE PROPOSED CLOSED-FORM SOLUTION

Flow rates were modelled with FDM for a number of randomly generated scenarios, varying hole radius, tailings permeability, pressure head, permeability ratio and anisotropy simultaneously.

The closed-form solution for each of these randomly generated scenarios was calculated using the charts/equations above and a comparison made.

As an example, estimation of the leakage rate through a hole with the following properties, is shown hereunder:

Table 4. Example problem input parameters

Head	**Anisotropy ratio**	**Hole Radius**	**$K_{tailings}$**	**$K_{foundation}$**
(m)	K_z/K_x	(mm)	(m/s)	(m/s)
99.2	0.15	1.38	7.934e-6	3.62e-6

The sequence of calculations using the derived closed-form solution is as follows:

- Determine permeability ratio = 4.57
- Find Q* (for isotropic conditions) = 2.352×10^{-3}
- Correct Q* for anisotropy ratio of 0.15 = $0.409 \times 0.15^2 - 1.189 \times 0.15$ = 61.5% reduction in flow
- Anisotropic Q* = $1.972 \times 10^{-3} \times (1-0.615) = 0.895 \times 10^{-3}$
- Calculate $Q = Q^*HK_{tailings}r = 9.71 \times 10^{-8}$ m^3/s = 8.39 l/day

A FDM simulation completed using the same input variables produced a flow rate of 8.85l/day.

Figure 8 shows the performance of the proposed closed-form solution compared to equivalent FDM analysis results, indicating errors typically less than 10%.

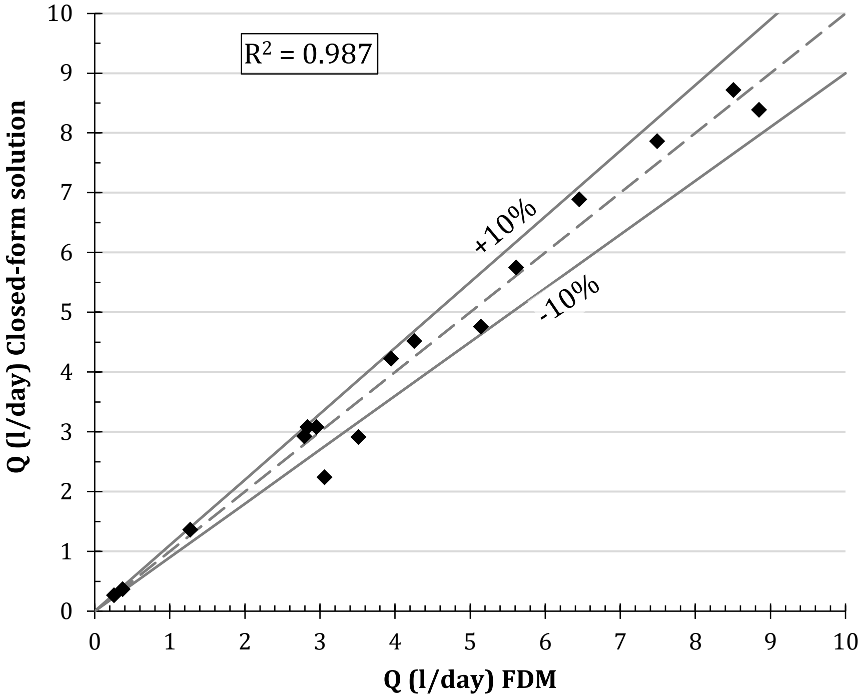

Figure 7. Performance measurement of the newly proposed method

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

A method to estimate leakage rates through geomembranes overlain by saturated tailings is proposed in this paper. This method builds upon existing relevant literature by including the effect of tailings anisotropy and the permeability ratio of the material overlying and underlying the GM.

The proposed method was derived through the Finite Difference Modelling of a wide range of scenarios considering leakage through a defect/hole in a GM.

The permeability ratio between the tailings and foundation material can be used to determine a normalised isotropic flow quantity (Figure 4). Correction of the normalised flow to account for tailings anisotropy is then considered as per Figure 6. A final flow rate is then calculated through multiplication of the normalised flow parameter with the corresponding hydraulic head, tailings permeability and hole radius.

The proposed method was validated though comparison against a series of random modelled scenarios. Corresponding leakage showed typical errors less than 15%.

5.2 Recommendations

Further verification work is required in the estimation of leakage rates though geomembranes overlain by saturated tailings. This includes the verification of the proposed method against experimental work.

Additional matters that should be considered upon undertaking of further work and application of the closed-form solution are listed hereunder. These are mainly associated with the underlying assumptions in the methodology of this paper:

1. Full contact is assumed between the tailings, foundation and GM. Hydraulic deposition of tailings onto a GM will likely lead to good contact conditions decreasing transmissivity between the GM and tailings. However, this may not be the case for interface between the GM and foundation material – especially with highly plastic foundation materials with a tendency to crack upon desiccation. The potential effect of transmissivity should therefore be considered in future work.
2. The migration of fines through the geomembrane may reduce the long-term leakage rate by clogging of the defect in the geomembrane. This effect is challenging to model and has not been considered. It is likely that, omission of the mentioned consideration in the modelled scenarios lead to conservative leakage rates.

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