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Leakage through a hole in a geomembrane beneath a fine-grained tailings

Yung-Chin (Alan) Chou ^{a,*}, R.W.I. Brachman ^{1, a}, R. Kerry Rowe ^a

ABSTRACT: Leakage through a 10-mm-diameter circular hole in a geomembrane beneath fine-grained tailings is examined for a range of pore pressures and effective stresses. Leakage was measured in an experiment with coupled physical and hydraulic conditions to simulate the effective stresses and flow conditions near the hole. The leakage rate was at little as 0.16 L/day with 200 kPa pore pressure (10-30 kPa effective stresses) and increased only to 0.46 L/day with 800 kPa pore pressure (200 kPa effective stress). Seepage analysis of the experiment and local measurements of permeability from small samples extracted after the experiment indicate that the tailings hydraulic conductivity controlling flow was $3\text{--}6 \times 10^{-9}$ m/s. Only a subtle decrease in hydraulic conductivity (less than 2 times) near the hole was found. No evidence of seepage induced migration of fines within the tailings was found. Calculations with the parameters deduced from the experiment show that leakage from a tailings storage facilities containing fine-grained tailings can be limited to 1-2 L/ha/day with a geomembrane liner, even when containing up to five 10-mm-diameter holes per hectare, as opposed to an unlined facility with 3 to 4 orders of magnitude more leakage.

Key words: geomembrane, leakage, tailings, physical modelling

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^a GeoEngineering Centre at Queen's–RMC, Queen's University, Kingston, ON K7L 3N6, Canada.

¹ Corresponding author: R.W.I. Brachman (email: brachman@queensu.ca).

* Present address: Sperling Hansen, 8-1225 East Keith Road, North Vancouver, BC V7J 1J3, Canada.

Introduction

Geomembranes are increasingly being used to line the bottom of tailings storage facilities to reduce the amount of flow from the tailings to the surrounding environment (McLeod 2016). The movement of water and the transport of dissolved contaminants through the geomembrane under a hydraulic gradient is limited to flow through holes that may develop in the geomembrane – this is termed as leakage. While much is known about leakage through geomembranes when used in liquid containment ponds (or lagoons) or as part of the base liners for solid waste landfills (e.g., Rowe 2012, 2005; Rowe et al. 2004; Giroud and Bonaparte 1989), leakage for tailings applications has received less attention and appears to be limited to the coarse-grained tailings considered by Rowe et al. (2017), Joshi et al. (2017) and Chou et al. (2018).

Conditions at the bottom of a tailings storage facility differ from those in a landfill and hence warrant separate consideration. Typically at the base of a landfill, there is a highly permeable drainage layer above the geomembrane to collect and remove leachate, and a very low permeable layer beneath the geomembrane (e.g., compacted clay or a geosynthetic clay liner) to reduce the leakage through any holes in the geomembrane. As such the head acting on top of the geomembrane is known and typically kept low (less than 0.3 m in many cases) and the material beneath the geomembrane is critical to obtaining composite liner performance to minimize leakage. In a tailings storage facility, the tailings can be placed directly on top of the geomembrane and, unless present on-site, the soil material beneath the geomembrane is unlikely to have low permeability. This means that the hydraulic head acting above the geomembrane is unknown and can be quite large, depending on the thickness of the tailings and depth of the pond above the tailings, and that the tailings themselves can provide resistance to leakage, depending on their hydraulic conductivity.

Leakage for some coarse-grained tailings applications has been investigated by Rowe et al. (2017). They conducted experiments where the total stress and pore pressure were controlled as boundary conditions on the top of a 0.3-m-thick layer of tailings above the geomembrane and the leakage through the geomembrane was measured. Three different coarse-grained tailings were examined, with up to 14, 27 and 45% finer than 75 μm by mass. They found that the leakage decreased as the fines content increased because of corresponding decreases in hydraulic conductivity of the tailings. However, the decrease in hydraulic conductivity alone were insufficient to account for the smaller leakage. They additionally reported a local decrease in hydraulic conductivity of the tailings near the hole from migration of fines towards the hole, particularly for the two tailings with the largest fines content, that was captured by their coupled physical and hydraulic laboratory model. Chou et al. (2018) extended this work to investigate the effect of having filter incompatible conditions between the coarse-grained tailings and soil material beneath the geomembrane. When combined with additional work by Brachman et al. (2017) and Joshi et al. (2017), there is now sufficient knowledge to permit rational design calculations for lined tailings storage facility for a range of coarse-grained tailings. Here, the conventional geotechnical definition of a coarse-grained is taken as having greater than 50% of its grains coarser than 75 μm by mass as per ASTM D2487-17.

However, questions remain as to the magnitude of leakage and factors controlling flow through a hole in a geomembrane when there are *fine*-grained tailings (greater than 50% of its grains finer than 75 μm) above the geomembrane. The distinction between tailings based on grain size is a starting point that may extend to consider plasticity, density and source of tailings as the available data base grows. Two mechanisms may possibly locally alter hydraulic conductivity near the hole and hence could affect leakage with fine-grained tailings. Because

head loss is locally concentrated above the hole, e.g., 75% of the head loss occurs within twice the radius of the hole (Brachman et al. 2017), there are large local increases in effective stress near hole. It may be postulated that these seepage induced effective stresses could locally reduce the hydraulic conductivity and thereby impact leakage through the hole. Additionally, the seepage velocity is very large near the hole, again because of the concentrated head loss. It is uncertain the extent to which fines can migrate from the localized seepage and impact leakage through the geomembrane.

The objectives of this paper, for one particular fine-grained tailings, are to: i) quantify flow through a 10-mm-diameter hole in the geomembrane at different combinations of pore pressure and effective stress, ii) investigate the parameters controlling flow through the hole, and iii) calculate leakage that may be expected through this type of hole for a lined tailings storage facility. In this paper, the results from a large (1-m-diameter) leakage experiment are reported. The hydraulic conductivity of the tailings is then deduced from numerical modelling of the leakage experiment and from permeability testing of local tailing samples extracted after the leakage test. Last, the inferred parameters are used in a numerical model with field-scale dimensions to calculate leakage for a lined tailings storage facility with fine-grained tailings.

Method and materials

Leakage test apparatus

The leakage test was conducted in a 1-m-diameter x 0.6-m-high pressure vessel, Fig. 1. Its diameter is 1.6 times larger and height is 1.2 times larger than the apparatus used by Rowe et al. (2017) to measure leakage for coarse-grained tailings, otherwise, the apparatus and methods were the same as those of Rowe et al. (2017). Brachman et al. (2017) showed with seepage modelling that the smaller 0.6-m-diameter x 0.5-m-high apparatus was able to simulate the

leakage and effective stresses near the hole relative to a distant boundary field case when the hydraulic conductivity of the tailings was taken equal to 5×10^{-9} m/s and that of the soil beneath the geomembrane was 1×10^{-7} m/s, for a 150 m thick layer of tailings with a 0.3 m deep pond above the tailings. The suitability of the larger apparatus to simulate leakage and local effective stresses for fine-grained tailings is confirmed subsequently in this paper after the parameters controlling flow are deduced.

Above the finite thickness (0.3 m) of tailings, total stress and pore pressure were prescribed as the top boundary conditions (Fig. 1). The total stress was applied by a pressurized rubber bladder that was clamped around its perimeter between the body and lid of the apparatus. The total stress simulates the weight of the overlying tailings. The pore pressure was controlled by pressurizing the open void space within two layers of highly permeable and saturated geocomposite drain with water. The geocomposite drain was observed to be dimensionally stable under the pressures tested. A uniform and known pore pressure was thereby imposed above the geomembrane, which is reasonable since it is located 30 times the hole diameter away from the 10-mm diameter hole. The effective stress imposed along the top surface of the tailings is the difference between the total stress and pore pressure.

Leakage was collected through an opening in the base of the apparatus. Outflow volume was measured to a precision of 50 mL. At this point, the head was maintained at the same elevation as the geomembrane (Fig. 1). The sides of the apparatus are sufficiently stiff in the radial direction such that radial effective stresses developed in the soil correspond to deep burial conditions. Friction treatment was applied along the sides to ensure that the applied bladder pressure acted on the geomembrane (Brachman and Gudina 2002). Total stresses within tailings at the elevation of the geomembrane are reduced by less than 3% from boundary friction with the

adopted friction treatment and 1-m-diameter of the apparatus based on calculations using three-dimensional arching theory (Brachman and Gudina 2002), such that the total stresses within the tailings are essentially uniform and equal to the applied pressure. Non-uniform effective stresses then develop in the coupled physical-hydraulic model near the hole according to the pore pressures developed from the induced flow. Preferential flow between the outer perimeter of the geomembrane and the sidewalls of the apparatus was prevented by using the same detail developed and validated by Brachman et al. (2017) involving a granular sodium bentonite seal. Inspection of the seal after completion of the leakage test showed no signs of sidewall leakage.

Materials

One particular non-segregating, fine-grained paste/thickened tailings from a copper-zinc mine (Lopes et al. 2013) were tested. Lopes et al. (2013) reported that the tailings are sulphide-rich, comprising 40 to 50% pyrite by mass with a very high net acid generating potential. The material tested was collected immediately downstream of a thickener plant and just upstream of the tailings delivery line to the storage facility. Lopes et al. (2013) reported that the bulk density coming from the tailings thickening plant ranged between 1.9 and 2 Mg/m³. Values at the time of sampling are not available. Additional details about the tailings have been reported by Lopes et al. (2013). The tailings tested had a fines content (% finer than 75 µm by mass) of 90%, Fig. 2. In terms of a soil classification, it would be considered a clay of low plasticity based on its liquid and plastic limits (Table 1) and conventional plasticity chart (ASTM D2487). Relative to the index properties of a few other fine-grained tailings documented in the literature, the material tested had a greater fines content than the two fine-grained (gold & coal) tailings reported by Qui and Sego (2001) and the two fine-grained (iron & copper) tailings reported by Hu et al. (2017) – 90% vs. 81 & 66% and 78 & 60%, respectively. The material tested had a lower liquid limit, but

similar plasticity index as the coal tailings (also classified as CL) from Qui and Sego – 26 & 16% vs. 40 & 15%, respectively. The liquid limit of the material tested (26%) was similar to the value of 28% for Hu et al.'s two fine-grained tailings and likewise for the plasticity indexes – 16% vs. 9 & 15%; but differ from the low-plasticity, sandy-silt hard-rock-mine tailings as reviewed by Vick and Bussière (2007). Other available geotechnical properties of the tailings are given in Table 1.

The tailings were transferred into the test cell from a barrel used for shipping, in which, the tailings had already settled out of solution, to a gravimetric water content of approximately 37% (73% solids). Since the particular tailings tested were non-segregating (Lopes et al. 2013), placing the tailings at a lower water content than in the field should still allow a reasonable simulation of field behaviour, especially at effective stress much greater than self-weight stresses in the barrel. The tailings were placed above the geomembrane in 10-to-20-mm-thick lifts and flattened using a trowel to remove air pockets and create a level surface for the next lift. The tailings were kept saturated during placement to minimize the potential for oxidation. The tailings did not segregate during placement. They were placed in this manner until a thickness of approximately 310 mm was reached. Grab samples of the tailings after placement gave a water content between 35% to 41% (saturated void ratio of 1.2 to 1.4 by taking a specific gravity of 3.5, which is the average value reported by Lopes et al. 2013) prior to loading. The gradation of the tailings retrieved upon exhumation (Fig. 2) were within the range reported by Lopes et al. (2013).

A 1-mm-thick, linear-low-density-polyethylene geomembrane (conforming to GRI 2015) with a centrally located 10-mm-diameter circular hole was tested to match the configuration investigated by Rowe et al. (2017) for coarse-grained tailings. The actual type and thickness of

geomembrane for use in any project would warrant evaluation of chemical and physical durability balanced with cost. This hole size is in the category of the most commonly observed defect size (0.5 to 2.0 cm²) from a database of electrical leak detection surveys (Nosko and Touze-Foltz 2000). Beneath the geomembrane, there was a 160-mm-thick layer of poorly-graded sand (Fig. 2). The sand was the same as that used by Rowe et al. (2017), who reported a hydraulic conductivity of around 10⁻⁵ m/s. Since much lower than that subsequently measured for the tailings, it is expected to have negligible head loss in the leakage test. The bulk density of the sand was 1650-1700 kg/m³. Its saturated moisture content was approximately 34%. The fine-grained tailings and sand subgrade were anticipated to be filter compatible, as the maximum ratio of D₁₅ in the sand to D₈₅ in the tailings was 3 (≤ 9 is required for no-erosion of silt and clay per Sherard and Dunnigan, 1989), where D₁₅ and D₈₅ are the grain sizes by which 15 and 85% of the soil is finer than by mass (Fig. 2). Filter compatibility between the tailings and underliner for the conditions tested was confirmed by post-test observations that showed no evidence of tailings penetrating sand. Further below the sand, a 140-mm-thick layer of commercially produced 9.5 mm rounded to sub-rounded uniform gravel (Pea gravel in Fig. 2) was placed as a filler material with negligible head loss. It was saturated prior to placement of the geomembrane and kept saturated for the duration of the leakage experiment. A nonwoven needle-punched geotextile (120 g/m²) was used to separate and obtain filter compatible conditions between the sand and pea gravel, as supported by post-test observations. Between the gravel and the base of the cell, another layer of the geocomposite drain was used to promote easy passage of fluid to the outflow port.

Small diameter permeameter

Seeing how Rowe et al. (2017) found a local decrease in tailings permeability near the hole, a small diameter sampler and permeameter was developed for this work in order to attempt to measure local values of hydraulic conductivity. The small diameter sampler and permeameter was designed to retrieve and permeate a specimen 8 mm in diameter and 6 mm in height in a small hollow tube (akin to a miniature Shelby tube) using the falling head, rising tailing water method. The tip of the tube thin was sharpened to minimize sample disturbance during insertion. The permeation test was conducted with the sample still contained within the sampling tube in order to minimize sample disturbance.

The 3-piece apparatus (Fig. 3), made of Stainless Steel-316, was designed such that the small samples could be loaded by compressing a carbon steel spring. Because the displacement of the spring was linearly related to the load, controlling the distance of the exposed external threads allowed the control of a specific load to be applied. However, as samples were one-dimensionally compressed, the compressed spring extends by the same distance as compression displacement, somewhat reducing the applied load. The sample thickness under load was estimated using a combination of the measured sample height after the test, and 1-D consolidation test results (Table 1). The applied load and hydraulic conductivity were then calculated using the estimated sample thickness. Since the specimens were loaded to effective stress levels corresponding to permeation stage 6 conditions prior to sampling, the recompression displacement were small and not believed to be impacted by friction between the sample and the sampling tube. Additional details have been given by Chou (2017).

The tailings supernatant was used as the permeant for all tests. The permeant was not de-aired and was open to the atmosphere during testing. As such, special care was given to

minimize trapped air in the apparatus during set-up. Also, evaporation and temperature were monitored throughout permeation such that the rising and falling head volumes could be tracked. Permeation continued until the back-calculated hydraulic conductivity was consistently within a range of uncertainty over four consecutive, typically daily, readings.

Results and discussion

Measured leakage

The combinations of total stress and pore pressure (u) imposed at the top surface of the tailings (Table 2, Fig. 4a) were selected to investigate the effects of: i) increasing pore pressure at a constant effective stress, and ii) increasing effective stress at a constant pore pressure. Fig. 4b shows the outflow volume collected over the first 20 weeks of permeation. The leakage was considered to be at steady-state once the cumulative outflow volume showed a linear trend with time (within 2%; shown as the solid lines in Fig. 4b). Steady-state flow was attained after 1 week of permeation for each phase. The slope of these trend lines provided leakage values (Q) for each phase of the test (Table 2).

Increasing pore pressure from Phase 2 to 3 by a factor of 2.5 (from 200 to 500 kPa) at a constant effective stresses of 30 kPa resulted in increased leakage by a factor of 2.27 (from 1.1 to 2.5 L/wk, Table 2). A further increase in pore pressure from Phase 4 to 5 by a factor of 1.6 (from 200 to 500 kPa) increased leakage by 1.54 times (from 2.4 to 3.7 L/wk) at an effective stress of 100 kPa. Pore pressure is the driving force for fluid flow through the system and theoretically, based on Darcy's law for one-dimensional flow through a porous medium and Forchheimer's equation for flow through a hole in a plate (e.g., see Rowe et al. 2004), flow would be expected to be directly proportional (i.e. 1:1) to pore pressure. The measured results are close to this expectation (Δu to ΔQ ratio of 1:0.91 for Phase 2 to 3 and 1:0.96 for Phase 4 to

5), but that they are less than 1:1 tends to suggest that the increase in pore pressure may also decrease material resistance to flow from seepage induced consolidation effects. Any such effect on leakage appears to be no more than 9% at 30 kPa effective stress and reducing to 4% at 100 kPa effective stress.

Where pore pressure is the driving force for flow, effective stress is the state parameter controlling the material resistance to flow (i.e., the compressibility and hydraulic conductivity of the tailings). Increasing effective stress with same the pore pressure was found to have much less effect than increasing pore pressure. At low effective stress, when effective stress was tripled from 10 to 30 kPa (Phase 1 to 2 with $u=200$ kPa) no effect on leakage was found, with values of 1.1 L/wk measured for each phase. When effective stress was doubled from 100 to 200 kPa (Phase 5 to 6 with $u=800$ kPa), leakage decreased by a factor of 0.86 (from 3.7 to 3.2 L/wk, Table 2). The decrease in leakage from Phase 5 to 6 is attributed to a decrease in hydraulic conductivity of the tailings from an increase in effective stress.

After 20 weeks, permeation during the final phase was continued to observe possible longer-term effects on leakage (Fig. 5). Total stress was maintained within 30 kPa and pore pressure within 20 kPa of the average values of 1000 kPa and 800 kPa, respectively. The initial linear regression of the Phase 6 data from week 17 to 20 (Fig. 4) appears to have been followed until about Week 28 after which a slight (5%), but discernable, reduction in leakage rate to 3 L/wk was observed for the remainder of permeation. The reduced leakage rate after 28 weeks suggests the hydraulic conductivity decreased slightly despite a relatively constant effective stress from secondary compression effects.

Given the 42 week duration of the permeation, only one large-scale leakage experiment was conducted. As such, it is not possible to comment on repeatability of the experiment. However,

some idea of repeatability of the apparatus and methods, albeit for different tailings, can be obtained by noting the very good repeatability (coefficient of variation < 15%) found by Rowe et al. (2017) for three leakage experiments on a coarse-grained tailings (details given in a subsequent section).

Seepage analysis

Axisymmetric, finite-element analysis using program SEEP/W (GeoStudio 2012) was used to interpret the measured results. More specifically, they were used to investigate what range of hydraulic conductivity (k) values can be inferred for the tailings (k_t), and to examine the impact of having lower a lower hydraulic conductivity (k_h) near the hole on both leakage and the effective stress conditions near the hole.

As in the experiment, zero radial flow boundaries were modelled along the test cell walls, the pore pressure was prescribed at the top surface of the tailings, and the head at the bottom of the test cell was kept constant and equal to the distance to the geomembrane (Fig. 6). The hole in the geomembrane was assumed to be filled with tailings. Element size near the hole was reduced until there was negligible effect (<1%) on calculated leakage. Following the analysis conducted by Brachman et al. (2017), no preferential lateral flow along the interface between soil and geomembrane elements was considered, meaning that any radial flow along the top surface of the geomembrane is quantified by the hydraulic conductivity of tailings. The hydraulic conductivity of the sand underliner was taken as 10^{-5} m/s as measured by Rowe et al. (2017). Since it is much more permeable than the tailings, uncertainty in its value did not impact the model results.

As a starting point, when assuming isotropic and uniform permeability throughout the tailings (i.e., $k_h=k_t$), hydraulic conductivity values of 6×10^{-9} to 4×10^{-9} m/s can be used to

reproduce the measured flows for the different permeation phases (Table 3). The dependence of hydraulic conductivity on effective stress is captured in the model by using a different value of k for each permeation phase as deduced from the seepage analysis.

Next, to investigate the impact of having lower permeability near the hole, the analysis was repeated but with the hydraulic conductivity of the tailings within a 10 mm radius from the hole (k_h) being one order of magnitude lower than that of the surrounding tailings ($k_h=0.1k_t$). The size of this region was selected based on having most of the head loss concentrated within one diameter of above the hole (Fig. 7), whereas the one order of magnitude decrease was judged to bound the maximum possible difference. In this case with nonuniform permeability, values of k_h between 4×10^{-9} and 3×10^{-9} m/s near the hole can be used to reproduce the measured flows (Table 3) when the corresponding k_t values away from the hole were between 4×10^{-8} and 3×10^{-8} m/s.

The similarities in k_h values near the hole between the two scenarios in Table 3 (different by no more than a factor of 1.5) illustrates that it is the permeability near the hole that governs leakage. The back-calculated values from these two scenarios suggest that, regardless of whether there is a significant decrease hydraulic conductivity near the hole, the hydraulic conductivity of the tailings within 10 mm of the hole at each phase was likely in the order of 3×10^{-9} to 6×10^{-9} m/s. These inferred values are consistent with the lower bound of measured hydraulic conductivity values for the gold (81% fines) and iron (78% fines) fine-grained tailings examined by Qui and Sego (2001) and Hu et al. (2017), respectively; but, smaller than those for the low plasticity sandy silt hard rock mine tailings reviewed by Vick and Bussière (2007).

The seepage analysis also provides insight into the effective stresses near the hole. To do this, contours of pressure head for the two permeability scenarios are first shown in Fig. 7. Since total stresses are essentially constant and equal to the applied pressure, effective stresses increase

where the pressure head decreases. The majority of the head loss occurs near the hole in both cases (Fig. 7). Having lower hydraulic conductivity near the hole (the nonuniform k scenario shown to the left of the centre line in Fig. 7) further concentrates the head loss near the defect. In either case, the pore pressure within the tailings that fills the hole is essentially zero, meaning the effective stresses in and near the hole are large and are very close to the applied total stress. The effective stresses are much lower at a distance of just 10 mm (i.e. one hole diameter) above the hole from the larger pore pressures. With uniform k , the pore pressure at this point is 65 m giving an effective stress of 350 kPa, while for the nonuniform k scenario, the pore pressure is 76 m and effective stress would be 240 kPa (both for the conditions that Fig. 7 was obtained with a total stress of 1000 kPa and pore pressure of 800 kPa applied at the top surface of the tailings).

Hydraulic conductivity and fines content near the hole

Six small diameter samples (A-D) were taken to measure the hydraulic conductivity near the hole to investigate if local variations in k from changes in effective stress or possible fines migration from the large seepage stresses could be detected. The location of the samples are shown in Fig. 8. These samples were taken after termination of the leakage experiment. Fig. 9 shows the retrieval of Sample A that contained the material filling the hole in the geomembrane. To reduce sample disturbance, they were permeated inside the same tubes that were used to extract the samples. Hydraulic conductivity was measured over a range of effective stresses inferred for each location based on the seepage analysis for Phase 6 of the leakage test (Table 4). Even though the samples are very small and because of the concentrated head loss near the hole, the effective stresses in the leakage experiment varied across the sample (e.g., from 500-1000 kPa for Sample A for the uniform k scenario; Table 4). While the initial focus of taking these

samples was measurement of k , grain size of Samples A, C and D were also obtained using laser diffraction.

Comparing the locations furthest (F) from and nearest (A) to the hole at their anticipated effective stresses during Phase 6 of the leakage experiment (i.e., Sample A when tested at 600-800 kPa vs. Sample F at 0 to 200 kPa, Table 4) shows that, on average, the k value at F (for 0-200 kPa) is 1.7 times that at A (for 600-800 kPa), Table 5. The difference is much more subtle, decreasing to 1.2 times on average, when using the results when tested at 200-400 kPa stress for Sample F (Table 5). Comparison of these two samples does support the hypothesis that local variations in k are developed in the leakage experiment, but the measured k values indicate that the difference is much more subtle than an order of magnitude difference.

A similar sort of comparison between local k values for Samples C and A – both concentric with the hole – at Phase 6 effective stresses (i.e., C at 0-200 kPa vs. A at 600-800 kPa, Table 4) leads to a similar observation that there may be a subtle difference in k , in this case 1.3 times on average (Table 5). Any such difference does not appear to be from fines migration this close to the hole as comparison of their post-test grain size distribution showed no discernable difference between these two locations (Fig. 10). This is consistent with the local k values for these two locations when compared at the same effective stress (600-800 kPa), as was no discernable difference in k between A and C was found ($2-4 \times 10^{-9}$ vs. $2-3 \times 10^{-9}$ m/s, Table 5), further suggesting that any local difference in hydraulic conductivity is from seepage induced changes in effective stress and not changes in fines content of the soil.

Overall, the local k measurements in Table 5 are consistent with the inference from the seepage analysis that the tailings hydraulic conductivity was on the order of $3-6 \times 10^{-9}$ m/s. The consistency between the deduced and measured k indicates that the modelling approach adopted

(i.e. without explicit modelling void ratio but by considering different values of hydraulic conductivity of the tailings) appears to be able to capture the dominant mechanisms controlling flow for the experiment conducted.

Extending the post-leakage test grain size comparison to include Sample D (located directly adjacent to the hole, Fig. 8) and an additional sample located concentric with the hole but 100 mm above Sample A (denoted as AA) showed that all had a similar grain size distribution (Fig. 10). When compared to the hydrometer samples (shown in Fig. 2), the laser diffraction samples appear to be marginally finer at the upper range of grain size (98% vs. 90% finer than 75 μm) but are more similar at the lower range (10-12% vs. 12% finer than 2 μm). These small differences could be attributed to the different testing technique (Segal et al. 2009). Based on all of the grain size tests, there is no evidence to suggest that a significant fines migration occurred near the hole for the particular fine grained tailings examined.

The development and application of the small diameter sampler and permeameter for the fine-grained tailings examined here was useful to show that there may only be a subtle difference in k (less than two times) near and away from the hole. Although beyond the scope of this work, it would be interesting to apply this local sampling technique for a case where local fines migration within a coarse-grained tailings are believed to impact the hydraulic conductivity near the hole to a much greater extent (e.g., by a factor of 60 for one of the tailings reported by Rowe et al. 2017).

Comparison with a coarse-grained tailings

The leakage test carried out in this study showed that when fine-grained tailings (hydraulic conductivity of around $3\text{--}6 \times 10^{-9}$ m/s) overlies a 10 mm diameter geomembrane defect and a filter compatible underliner, the leakage through the defect was less than 0.5 L/day for the pore

pressures and effective stresses tested. A comparison of the leakage rate between this study and the silty-sand tailings (bulk hydraulic conductivity, i.e., away from the hole, in the order of 10^{-7} m/s) reported by Rowe et al. (2017) for the same defect size was made (Table 6). For reference, the silty-sand had a fines content ($\% < 75$ mm) of 26% relative to 90% for the fine-grained tailings. As expected, the leakage is smaller with the fine-grained tailings, but the decrease in leakage is not directly proportional to the decrease in hydraulic conductivity. In this comparison, a 20 times difference in k resulted in 6-10 times difference in leakage. This is a reflection that the local k near the hole with the silty-sand tailings likely decreased more relative to the material away from the hole than for these fine-grained tailings. Rowe et al. (2017) found that a 6 fold decrease in local k near the hole (from 1.1×10^{-7} to 2×10^{-8} m/s) was required to match the measured flow based on similar seepage modelling as that used in this work, relative to a factor less than 2 for these fine-grained tailings. The silty-sand tailings likely achieved lower than expected leakage rate (based on bulk hydraulic conductivity alone) due to a suffusive component of the tailings that migrated towards and deposited near the hole, whereas, in this study, a smaller reduction in k from a local increase in effective stress appears to have a more subtle influence on leakage.

Practical applications

Additional finite-element seepage modelling was conducted to compare the leakage calculated with field-scale dimensions with those measured and calculated with the laboratory scale dimensions. Like the laboratory model, the field case considers only a single isolated 10-mm-diameter circular hole. The field case considers flow through the full thickness of the tailings (T), whereas in the physical model there is a finite thickness (0.3 m) of tailings above the geomembrane where the pore pressure is then prescribed as a boundary condition and the weight

of the overlying tailings also a prescribed boundary condition by applying a uniform pressure. The field case also considers flow through the tailings out to a radial distance from the centre of the hole of $R=50$ m, at which point there is a zero radial flow boundary (Fig. 11). The k values for the uniform permeability case from Table 3 were used, thereby neglecting the effect of any subtle decrease in k near the hole. For the three cases in Table 7, there was no significant difference in leakage between the field scale with $R=50$ m and the laboratory scale, confirming that the laboratory dimensions are sufficient to have negligible boundary effect on flow through the 10-mm-diameter circular geomembrane hole relative to the distant boundary case.

Inclusion of another modelling case with $R = 10$ m (Fig. 11) in Table 7 shows that having the radial boundary out to 50 m is sufficiently far away from the hole to capture the distant boundary case. Key to effectiveness of the reduced scale of the laboratory model seems to be capturing the aspect ratio of radius to thickness of the tailings. This is illustrated by the additional two cases in Table 7 with $R = 1$ (Fig. 11) and 0.5 m, but with no change to the thickness of tailings, where the flow would deviate from the distant radial boundary case.

While the prospect of having a single, isolated hole in the geomembrane is one possible field scenario, consideration is also warranted to consider the effect of having multiple holes per hectare. For example, assumption of 5 holes per hectare is common in engineering design for the cases anticipated to have good construction quality control and assurance (e.g., see Rowe 2012). The seepage model results in Table 7 can also be used to assess when one hole can impact the flow from another as follows. If there were 5 equally spaced holes per hectare over a large area, then the distance between the equally spaced holes would be 20 m. In all three cases in Table 7, the model results with $R = 10$ m are equal to the distant boundary case, meaning that – if equally spaced – one of the holes would not be affected by the other 4, and the leakage per hectare would

simply be 5 times the single isolated hole with distant radial boundaries. Holes spaced at least 2 m apart for Case 1 (i.e., 2 times $R = 1$ m) and 20 m apart for Cases 2 and 3 (i.e., 2 times $R = 10$ m) would be far enough based on the model to not have an influence on another hole.

Calculations of leakage (Q) using the W-F equation (Wissa and Fuleihan 1993):

$$Q = \frac{2 k h d}{1 + \frac{8}{\pi} \left(\frac{t}{d} \right)} \quad [1]$$

where: k is the hydraulic conductivity of the tailings above the geomembrane (assumed to be uniform), h is the head above the geomembrane, t is the geomembrane thickness and d is the diameter of the hole in the geomembrane, are also included in Table 7. As explained by Badu-Tweneboah and Giroud (2017) this approach uses Darcy's Law to capture flow through the tailings contained within the hole and Forchheimer's equation for flow through tailings above the hole. It neglects resistance to flow from the material beneath the geomembrane. Values obtained with the W-F equation match the distant boundary field values for all three cases in Table 7. This equation can be used for practical purposes for the fine tailings and conditions examined in this paper since there was no significant localization in k near the hole and the underliner beneath the geomembrane provided no resistance to flow. This differs to some of the coarse-grained tailings examined by Rowe et al. (2017) where Badu-Tweneboah and Giroud (2017) found that the W-F equation resulted in values much greater than the measured leakage.

Last, calculations of leakage for a geomembrane lined and unlined tailings storage facility are compared in Table 8. It was assumed that there are 5 holes per hectare, the hole diameter is 10 mm, the holes are far enough apart such that they do not interact with each other, the holes do not coincide with a geomembrane wrinkle, the tailings are the same as those tested, the tailings and subgrade are filter compatible and that the pond depth is less than 30 m above tailings. The flow through the geomembrane was obtained from the values measured in the leakage

experiment for the loading phases tested. Leakage for the unlined case without a geomembrane was obtained with Darcy's Law using the same hydraulic conductivities as the uniform permeability scenario (Table 3).

For each loading phase, the leakage without the geomembrane is substantially larger than that for the geomembrane lined case (Table 8), ranging from 13,000 times larger for the first two phases (effective stress 10-30 kPa, 200 kPa pore pressure) to 2,400 times larger for the final two phases (effective stress 100-200 kPa, 800 kPa pore pressure). Calculations for the unlined case decrease with higher stresses, whereas those for the geomembrane lined case increase. This is because of the different hydraulic gradients between the two cases. For the case with a geomembrane defect, the pressure head is dissipated over a very short distance compared to the unlined case, and this distance does not change much for the different phases of operation. However, for the case without geomembrane, it is assumed that the pore pressure dissipates across the full thickness of tailings (ignoring reducing hydraulic conductivity with depth). Thus, the leakage reduces with each phase, as the pond depth becomes smaller relative to the tailings thickness. Overall, the results suggest that should the geomembrane remain reasonably intact (i.e., only a few holes per hectare) during the design life of the facility (i.e., the service-life of the geomembrane equals or exceeds the design life of the facility, e.g., see Rowe 2005, 2012), it can be a very effective hydraulic barrier for tailing storage facilities containing fine-grained tailings similar to the one tested in this study.

Hole size

Leakage was measured for only one hole size (10-mm-diameter). The effect of hole size on leakage is examined here from the theoretical calculations and measurements with a coarse-grained tailings presented in Table 9. For the fine-grained tailings investigated in this paper,

leakage with different hole sizes was calculated using the W-F equation (Eqn 1), which was found to match the measured flows in Table 7 with a maximum difference of 4%. For Phase 6 conditions (50 m tailings thickness, 30 m pond depth) and the k deduced from seepage modelling and measurements on the tailings samples ($k = 4 \times 10^{-9}$ m/s), decreasing hole diameter from 10 mm by one-half to 5 mm, decreases the calculated leakage by factor of 0.4, while doubling the hole diameter from 10 to 20 mm, increases the calculate leakage by a factor of 2.1 (Table 9).

This calculated trend with hole size is similar to landfill conditions (where there is low head and permeable drainage layer above the geomembrane, and low permeable material below geomembrane) if perfect contact between the geomembrane and underlying clay is assumed, Table 9. With perfect contact, leakage is theoretically proportional to hole size using Forchheimer's equation (e.g., see Rowe et al. 2004). However, after over a decade of field monitoring of landfill liners (Bonaparte et al. 2002; Rowe et al. 2004; Rowe 2012) it is generally accepted that the effect of hole size diminished when there is a transmissive layer allowing lateral flow along the interface between the geomembrane and underlying clay, especially for small holes, as lateral flow below the geomembrane results in leakage through the clay over a larger area. When considering a transmissive layer for good – but not perfect – contact conditions (parameters and results given in Table 9), the calculated values from Rowe et al. (2004) show only a 1.5 fold increase in leakage when the diameter increases by 13 times from 1.5 mm to 20 mm. As explained by Rowe et al. (2004), lateral flow below the geomembrane results in leakage through the clay over a larger area than just that of the hole. The transmissive zone occurs for landfill conditions by placing the geomembrane on top of a prepared clay surface that has some irregularities (e.g., see Rowe et al. 2004). The placement of the particular fine-grained tailings tested with an initial high water content on top of the geomembrane (as done in

the leakage experiment) does not seem to result in a more interface more transmissive than that of the hydraulic conductivity of the tailings as the tailings would be allowed to better conform to the geomembrane surface. Further, there is no indication that there was a transmissive zone between the fine-grained tailings and the geomembrane in the leakage experiment as both the seepage model and W-F equation were able to reproduce the measured leakage without considering preferential flow along the interface. Values in Table 9 are very low for the fine-grained tailings, especially relative to those if there was no geomembrane.

For a coarse-grained tailings (with 26% fines), Rowe et. al (2017) found the measured leakage to be insensitive to hole size for 10- and 20-mm diameter holes, Table 9. These results were obtained for much greater effective stresses (1500 kPa) and pore pressures (1500 kPa) than for the Phase 6 conditions examined here for the fine-grained tailings (Table 6) and as noted by Rowe et al. (2017) their measured leakage was impacted by a suffusive migration of tailing fines to the hole. Their measured flow reduced by up to three orders of magnitude for the 1.5-mm-diameter hole they examined (Table 9). As previously noted, no evidence of seepage induced migration of fines within the fine-grained tailings was found. While additional measurements of leakage through different hole sizes with fine-grained tailings would certainly be useful to corroborate the calculations in Table 9, use of the simple W-F equation to quantify the effect of hole size on leakage seems like a reasonable first approach given the lack of preferential interface flow and fines migration, and with the use of the deduced k from the leakage experiment for the particular fine-grained tailings examined.

Conclusion

Leakage through a 10-mm-diameter hole in a geomembrane beneath a fine-grained tailings was examined to quantify the possible magnitude of flow through a lined tailings storage facility

and to investigate the factors impacting flow through the hole. Leakage was measured in a 1-m-diameter laboratory experiment with coupled physical and hydraulic conditions that were shown with numerical modelling to simulate field conditions for the cases examined. Numerical modelling was also used to interpret the results from the leakage experiment and to calculate leakage for practical cases. For the particular fine-grained tailings examined (90% finer than $< 75 \mu\text{m}$ by mass; initial solids content of 73%) and conditions tested, it can be concluded that:

- i. leakage started low (only 0.16 L/day at effective stresses of 10-30 kPa and 200 kPa pore pressure) and remained low (0.46 L/day at an effective stress 200 kPa and 800 kPa pore pressure) over the 42 week duration of the experiment;
- ii. increases in pore pressure, as the driving force for flow, had a much greater effect on leakage than increases in effective stress; increasing pore pressure by factors of 2.5 and 1.6 increased leakage by factors of 2.3 and 1.5 at constant effective stresses of 30 and 100 kPa, whereas, at most, leakage decreased by a factor of 0.86 when effective stress doubled from 100 to 200 kPa with a pore pressure of 800 kPa;
- iii. despite the very large hydraulic gradient and large increases in effective stress just above the hole, there was no evidence of seepage induced migration of fines within the tailings and only a subtle decrease in k (less than $\times 2$) near the hole was found based on grain size and permeability testing of local tailing samples extracted after the leakage test;
- iv. seepage analysis and local measurements of permeability suggest that the tailings hydraulic conductivity controlling flow was $3\text{--}6 \times 10^{-9} \text{ m/s}$; and
- v. leakage from tailings storage facilities containing fine-grained tailings can be limited to as little as 1-2 L/ha/day with a geomembrane liner even when containing up to five 10-mm-

diameter holes per hectare, as opposed to an unlined facility with leakage upwards of 6,000 to 10,000 L/ha/day.

The paper has provided new insight regarding leakage through a 10-mm-diameter hole in a geomembrane beneath one particular fine-grained tailings. However, like most research it also raises questions for future study such as what is the effect of hole size and shape as well as tailings plasticity and density? How does k vary with fines content and void ratio? How well can results from independent test be used to predict the details of the behaviour in these large scale tests? These questions are presently the subject of ongoing research at Queen's.

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Figure Captions

Fig. 1. Laboratory apparatus used to measure leakage.

Fig. 2. Gradation of materials used in the leakage test.

Fig. 3. Small diameter permeameter developed to measure local values of hydraulic conductivity.

Fig. 4. a) Total stress and pore pressure applied at to the top surface of the tailings, b) measured outflow.

Fig. 5. a) Total stress and pore pressure applied at to the top surface of the tailings, b) measured outflow during Phase 6 past 20 weeks.

Fig. 6. Boundary conditions for seepage analysis. Select flow lines and 80 m pressure head contour shown for permeation Phase 6 and uniform tailings $k = 4 \times 10^{-9}$ m/s.

Fig. 7. Contours of pressure head (5 m intervals) near the geomembrane hole for Phase 6 with: a) local decrease in permeability near hole (shown to the left of the centre liner), and b) uniform permeability (shown to the right of centre). Scale 1H:1V.

Fig. 8. Approximate location of 6 samples retrieved from tailings near the geomembrane hole (superimposed on pressure head contours, m, from Fig. 6a.). Scale 1H:1V.

Fig. 9. Photograph of bottom surface of geomembrane showing retrieval of Sample A (small stainless steel tube pushed into geomembrane hole). A technique was developed such that a column of tailings above the geomembrane hole could be retrieved with little disturbance to the area. The geomembrane could then be cut and flipped over such that the hole location could be revealed through careful excavation. Scale is in centimetres. r denotes the distance from the centre of the hole.

Fig. 10. Gradation of materials from small diameter permeameter samples.

Fig. 11. Geometries considered to examine the distance to the radial boundary (R) for: (a) Case 1, (b) Case 2, and (c) Case 3.

Notes: Tailings dimension shown was measured immediately after placement.
 σ = total stress, u = pore pressure, LLDPE = linear-low-density polyethylene.
 r = distance from centre of the hole and apparatus.

Fig. 1. Laboratory apparatus used to measure leakage.

Fig. 2. Gradation of materials used in the leakage test.

Fig. 3. Small diameter permeameter developed to measure local values of hydraulic conductivity.

Notes: Pressure readings shown are ± 4.5 kPa.
 Incremental leakage reading shown are ± 1 mL.
 The test was paused prior to Phases 2 and 5 so that the lid could be removed to place additional filler sand.
 Fluid supplying σ was changed during Phase 6 (before week 19) from air to water for practical reasons.

Fig. 4. a) Total stress and pore pressure applied at to the top surface of the tailings, b) measured outflow.

Notes: Pressure readings shown are ± 4.5 kPa.
Incremental leakage reading shown are ± 1 mL.
The linear regression plotted uses data from Phase 6 prior to 20 weeks, shown in Figure 4.

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Table 1. Properties of fine-grained tailings examined

Property	Value
Coefficient of consolidation – vertical ^a	1×10^{-5} to 5×10^{-7} m ² /s
Coefficient of consolidation – horizontal ^b	1×10^{-4} to 4×10^{-6} m ² /s
Primary compression index ^a	0.20 to 0.25
Secondary compression index ^a	0.002 to 0.005
Recompression index ^c	0.02 to 0.04
Liquid limit	26%
Plasticity index	10%
USCS classification	CL
Specific gravity ^b	3.2 to 3.6

- a. Coefficient of consolidation and compression indices reported are based on four 1-D consolidation tests (ASTM D2435). Load increments were approximately 20 kPa, 100 kPa, 200 kPa, 400 kPa, 700 kPa. Typical normally consolidated soil behavior was observed for the increments tested. Void ratio between 1 to 0.65.
- b. Reported by Lopes et al. (2013).
- c. Recompression was only performed for two of the four consolidation tests. The recompression index was based on unloading each load increment to seating load (approximately 1 kPa), and reloading back to the increment.

Table 2. Imposed top boundary conditions and measured leakage

Phase	Total stress (kPa)	Pore pressure u (kPa)	Effective stress (kPa)	Leakage Q (L/wk)
1	210	200	10	1.1
2	230	200	30	1.1
3	530	500	30	2.5
4	600	500	100	2.4
5	900	800	100	3.7
6	1000	800	200	3.2

Note: Target values are shown. Average total stress and pore pressure were kept to within 11.5 kPa of values presented above. Average vertical effective stress were within 4.5 kPa for Phase 1-3, within 13.5 kPa for Phase 4 and 5, and within 20.5 kPa for Phase 6. The imposed hydraulic gradient from the top surface of the tailings to the top of the underliner was 65, 161 and 258 for the three values of pore pressure examined.

Table 3. Hydraulic conductivity k_h ($\times 10^{-9}$ m/s) of tailings within 10 mm of the hole inferred from seepage analysis

Phase	Uniform	Local decrease
	permeability $k_h = k_t$	near hole $k_h = 0.1k_t$
1	6	4
2	6	4
3	5	4
4	5	4
5	5	4
6	4	3

Note: k_t is the hydraulic conductivity of the tailings away from the hole. The hydraulic conductivity of the soil beneath the geomembrane was taken to be 1×10^{-5} m/s based on Rowe et al. (2016).

Table 4. Effective stresses (kPa) at sampling locations during Phase 6 inferred from seepage analysis

Sample location	Uniform permeability $k_h = k_t$	Local decrease near hole $k_h = 0.1k_t$
A	500-1000	450-1000
B	400-500	350-400
C	350-400	200-250
D	300-650	200-400
E	300-450	200-250
F	300-350	200

Table 5. Local measurements of hydraulic conductivity ($\times 10^{-9}$ m/s)

Stress (kPa)	Sample A	Sample B	Sample C	Sample D	Sample E	Sample F
0-200	-	3-5	3-5	4-6	-	4-6
200-400	-	2-4	-	2-3	3-4	3-4
600-800	2-4	1-2	2-3	-	1-2	-

Table 6. Comparison of leakage (L/day) between fine-grained tailings tested and a silty-sand tailings reported by Rowe et al. (2017)

Pond level (m) ^a	Fine-grained tailings $k \cong 3\text{-}6 \times 10^{-9}$ m/s	Silty-sand tailings $k \cong 1 \times 10^{-7}$ m/s
20	0.2	1.2-1.3 ^b
50	0.3-0.4	2.7-3.6 ^c
80	0.5	-
100-150	-	2.4-6.5

- a. Pond level refers to the simulated thickness of tailings plus pond depth above the tailings.
- b. The effective stress imposed on top of the tailings is 20-40 kPa higher in Rowe et al. (2017).
- c. The effective stress imposed on top of the tailings is 400-470 kPa higher in Rowe et al. (2017).

Table 7. Effect of radial distance to boundary on calculated leakage (L/day) through 10 mm diameter hole.

Calculation	Distance	Case 1	Case 2	Case 3
	to radial	$T=10\text{ m}^b$	$T=30\text{ m}$	$T=50\text{ m}$
	boundary	$P=10\text{ m}^c$	$P=20\text{ m}$	$P=30\text{ m}$
	R (m)	$k=6\times10^{-9}\text{ m/s}$	$k=5\times10^{-9}\text{ m/s}$	$k=4\times10^{-9}\text{ m/s}$
Lab-scale seepage model ^a	0.5	0.16	0.34	0.46
Field-scale seepage model	50	0.16	0.34	0.45
	10	0.16	0.34	0.45
	1	0.16	0.31	0.40
	0.5	0.14	0.21	0.22
W-F equation ^d	–	0.16	0.34	0.44

- a. Finite thickness of tailings above the geomembrane = 0.3 m.
- b. T is the thickness of tailings above the geomembrane.
- c. P is the depth of the pond on top of the tailings.
- d. Calculated using $h = T + P$ and $t = 1\text{ mm}$.

Table 8. Calculate leakage for lined and unlined cases.

Loading phase	Lined ^a	Unlined ^b
	(L/ha/day)	(L/ha/day)
1-2	0.8	10,400
3-4	1.7	7,200
5-6	2.3	5,500

- a. With geomembrane. Assuming five 10 mm diameter holes per hectare.
- b. No geomembrane. Assuming the same tailings hydraulic conductivities as leakage with the geomembrane.

Table 10. Effect of hole size on leakage (L/day).

Hole diameter (mm)	Fine-grained tailings ^a	Coarse-grained tailings ^b	Landfill perfect contact ^c	Landfill good contact ^d
1.5	0.03	0.005	0.0001	0.38
5	0.18	-	0.0003	0.45
10	0.46	5	0.0005	0.51
20	0.98	5	0.0010	0.58

a. Calculated with W&F equation (Eqn. 1) with $k = 4 \times 10^{-9}$ m/s, $h = 80$ m, $t = 1$ mm.

b. Measured by Rowe et al. (2017) for pore pressure = 1500 kPa, effective stress = 1500 kPa.

c. Calculated with Forschheimer equation (Rowe et al. 2004) with $k = 1 \times 10^{-9}$ m/s, head on liner = 0.3 m.

d. Calculated by Rowe et al. (2004) with $k = 1 \times 10^{-9}$ m/s, interface transmissivity between the geomembrane and clay = 1.6×10^{-8} m²/s, head on liner = 0.3 m, liner thickness 0.6 m, head below liner = 0.