Canadian Geotechnical Journal
 Revue canadienne de géotechnique

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 Defect under Filter Incompatible Conditions**

Journal:	<i>Canadian Geotechnical Journal</i>
Manuscript ID	cgj-2017-0602.R1
Manuscript Type:	Article
Date Submitted by the Author:	14-Feb-2018
Complete List of Authors:	Chou, Alan; Queen's University, Kingston, Civil Engineering Rowe, Kerry; Queen's University, Civil Engineering Brachman, Richard; Queen's University, Kingston, Civil Engineering
Is the invited manuscript for consideration in a Special Issue? :	N/A
Keyword:	Piping, Tailings, Geomembrane, Leakage

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Erosion of Silty Sand Tailings through a Geomembrane Defect under Filter Incompatible Conditions

by

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Abstract

At tailings storage facilities, a geomembrane may be used to contain tailings from relatively more permeable foundation or embankment materials. A filter incompatible condition may arise between the tailings and underliner materials. In this study, potential for piping erosion of tailings through a 1 cm diameter geomembrane defect was evaluated in a series of physical experiments. The geomembrane defect was sandwiched between silty sand tailings, and various underliners ($DF_{15}/DB_{85}=5.6$ to 13.5) not meeting typical retention criteria for filtration. The leakage rates and visual findings revealed that a critical stress condition existed where erosion continuously occurred for up to 24 hours. This stress condition could be encountered during early deposition or development of a reclaim pond at a tailings storage facility. When allowed to occur, erosion during this stress condition resulted in subsequent leakage rates that were 2 to 3 orders of magnitude higher than previously observed with filter compatible conditions and higher stresses. Practitioners unaware of this potential for erosion near the defect may significantly underestimate leakage and under-predict pore pressures within the embankment.

Key words: Piping, Geomembrane, Tailings, Embankment, Leakage

Introduction

Geomembranes have been used in the mining industry since the 1980s (Vick, 1990). At tailings storage facilities (TSFs), geomembranes can be used to reduce seepage from the facility into the surrounding environment, and/or reduce the hydraulic gradient within the embankment. Figure 1 illustrates the use of a geomembrane at a TSF.

Research into landfill applications has shown that defects govern leakage through geomembranes. Because the presence of some defects is common even in well-designed and constructed facilities, an allowable amount of defects is often factored into design (e.g., Giroud and Bonaparte 1989a,b; Giroud 1997; Rowe et al. 2004; Giroud 2016). The leakage resulting from these defects in landfill facilities can then be estimated using equations presented in Rowe (1998, 2012). However, the presence of tailings results in a configuration in which a free-draining layer may not be present immediately above the liner (Figure 2), making the equation less applicable.

Little had been published on the leakage phenomenon arising from the above configuration until recently. Rowe et al. (2016) studied the leakage rate through such a configuration in 60 cm diameter rigid-wall permeameters called Geosynthetic Liner Longevity Simulators (GLLS). Permeation tests were performed for silty sand tailings overlying a geomembrane with a defect, under typical stresses found in TSFs. The study found that the leakage rates are likely less than tens of litres a day for defects up to 20 mm in diameter. Similar leakage rates were found when a wrinkle existed at the defect (Joshi et al. 2016). However, these leakage rates were contingent on a filter compatible subgrade with the tailings. In a TSF which may cover hundreds of hectares, filter compatible subgrade may not exist onsite without significant earthworks. Thus, there is an incentive to assess leakage behavior under filter incompatible conditions.

In one of the tests performed on a 10 mm diameter defect overlying a uniform pea gravel underliner, Rowe et al. (2016) observed that tailings migrated through the underliner, and a cavity formed in the tailings (Figure 3). This result prompted the question of whether the defect facilitates erosion under filter incompatible conditions because of the presence of a concentrated point of seepage. Thus, the objective of this paper is to explore the potential for erosion of silty sand tailings beneath a lined TSF at locations where the foundation materials are filter incompatible with the tailings. The paper also examines the degree to which erosion could occur under various stress conditions that could be experienced at a TSF.

An illustrative seepage model

The effect on hydraulic gradient (therefore velocity) due to a defect in a geomembrane can be illustrated using an axisymmetric finite element (FE) model for saturated Darcy flow. The modelled material parameters and boundary conditions are given in Table 1.

For the 10 mm-diameter defect modelled, the majority of the head dissipation occurred within approximately 50 mm of the defect (Figure 4). As a result of the concentrated radial dissipation of pressures near the hole, hydraulic gradients of about 2,000 occur at 5 mm above the hole and exceed 5,000 at the defect. This is much higher than typical gradients expected in an earth dam, and suggests the gradients near the hole could facilitate movement should the underliner be filter incompatible.

Below the geomembrane, a similar pattern of pressure dissipation occurs, but at much smaller magnitude (Figure 5). The resulting hydraulic gradient diminishes from 6 immediately below the defect to about 2, five millimetres below the defect, and as small as 0.02 approximately 100 mm below the defect. At gradients around 0.02, it is questionable whether sufficient seepage force exists to move tailings particles through the large voids in the underliner since Skempton and

Brogan (1994) observed that upward piping of an internally unstable sandy gravel occurred at a gradient of 0.2. Thus, erosion is more likely to stop in the underliner as a result of the presence of the defect.

Based on the illustrative model, the defect both facilitates and limits erosion from the perspective of hydraulic gradient; however, it is not clear which effect would govern. Furthermore, although the model shown is useful to illustrate the pore pressure dissipation, it does not account for:

- a contact dependent transmissive layer that may develop between the geomembrane and underliner, or
- changes to hydraulic conductivity that may occur due to localized tailings movement.

Thus, a test program (described in the next section) was conducted to assess this effects of the extremely different gradient above and below the defect in the geomembrane. The objective of the test program, was to:

- obtain estimates of leakage rate under filter incompatible conditions for the configuration shown in Figure 2; and
- assess whether existing methods adequately predict erosion behavior when filter incompatible materials sandwich a geomembrane defect.

Test Program

GLLS Apparatus

The test apparatus used in this study was substantially the same as the GLLS used in Rowe et al. (2016). The GLLS was essentially a large rigid-wall permeameter. It comprised a 0.5 m long, 0.6 m diameter section of a stainless steel pipe sealed by blind flanges on both ends (Figure 6). Ports drilled through the flange plates and pipe wall allowed plumbing attachments (gauges, valves,

regulators, etc.). These attachments facilitated independent control of boundary conditions which defined the steady state conditions in the cell:

- total vertical stress – σ_v
(applied using air above a rubber bladder that seals the air from pipe contents);
- pore water pressure above the tailings layer– u_a
(applied using water above the tailings layer)
- pore water pressure in the underliner layer)– u_b
(between 6 cm to 17 cm below the geomembrane)

The test apparatus allowed the operator to control a specific vertical effective stress, σ_v' . When the desired stresses were reached, leakage through the underliner was collected from an outflow tube downstream of a geocomposite drain below the underliner, and overflow tubes on the sides of the GLLS.

The rate of leakage was used as an indicator of whether erosion was taking place inside the GLLS. A stable (non-eroding) result was defined as a test in which leakage readings (typically averaged at least hourly) did not vary by more than 15% for at least 3 hours. It is noted that this definition does not necessarily mean the material will be stable in the time scale of real TSFs, but provides an indication. An unstable result was defined as a test in which the leakage did not meet the stable definition for more than 20 hours, or if an obvious erosion void was observed at the surface of the tailings upon exhumation.

To prevent seepage along the circumference of the geomembrane, a sodium bentonite seal was placed around the geomembrane. The sealing technique was as described by Brachman et al. (2016) and successfully applied in Rowe et al. (2016). Another technique that was adopted from previous work is the use of friction treatment as applied in Tognon et al. (1999). The treatment comprised attaching two 0.1 mm thick polyethylene sheets lubricated with grease to the pipe

wall. Brachman and Gudina (2002) calculated that the treatment allows 95% of the total stress applied to the bladder to act on at the geomembrane elevation.

Comparison with traditional filtration test apparatus

Since one of the objectives of the study was to assess if existing methods can be used to predict erosion behavior for the case of geomembrane defects, it is useful to explore similarities between the tests used to establish modern retention criteria and the proposed apparatus (Table 2).

Foster and Fell (2001) presented three test configurations performed by Sherard et al. (1984, 1989) used to establish modern filter design methods (USBR 1987; USDA-SCS 1994). The three configurations are known as the no-erosion test (NEF), slot test, and slurry test (Figure 7 shows illustrations of the NEF and slurry test). These tests were developed in the 1980s to identify the factors governing successful filtration of silts and clays (typically used as dam cores). Generally, all three test configurations comprised of a hollow cylinder containing the base (the dam core material being evaluated) and its potential filter. Around the perimeter of the filter, a material much finer than the filter was placed to prevent the base from piping along the perimeter cylinder wall (wall seal in Figure 7). After all materials were placed, the simulated dam core and filter were subjected to up to 400 kPa of water pressure. A successful/unsuccessful filtration result could then be identified (within minutes) by observing whether the flowrate quantity and turbidity came to equilibrium.

The main difference between the tests were in how the base was prepared and the orientation of seepage. The slurry test differed from the slot and NEF test in that the base was placed as a slurry (typically diluted to 2.5 times its Liquid Limit) to account for possibility of the base eroding down to its basic particles (rather than clods). For the slot and NEF test, a fully penetrating pipe in the base material was created to account for the possibility of a hydraulic

fracture in the dam core due to differential settlement (Sherard 1986). The two differed in that the slot test was an earlier version of the NEF test with a larger pipe (a slot with section dimensions 1.5 mm x 12.7 mm), and was of horizontal orientation rather than vertical. The NEF was developed later in the research program to allow for quantification of the erosion, which allowed the development of a “no-erosion” criteria. The criteria has since been widely adopted as the design retention criteria for granular filters.

The GLLS filtration tests had some similarities with these traditional filtration tests. The assumption of hydraulic fracturing of the base material (analogous to tailings from this study) in the slot and NEF tests induces a defined location of pore pressure dissipation near the filter-base interface, which has a similar effect to the presence of a geomembrane defect (as discussed using the illustrative model). However, the base material in the slot and NEF tests were compacted to simulate a dam core, whereas the tailings in the GLLS test experienced a stress path related to its continuous deposition and the build-up of head for submerged tailings. Similar to the slurry test, tailings in the GLLS test were initially placed as a slurry prior to inducing stress. Table 2 summarizes the key differences between the various filtration test configurations.

It follows from the foregoing that the new apparatus can be considered a combination of traditional test configurations. However, there are some important issues associated with this study that cannot be addressed by the traditional tests, viz:

- There is a transmissive layer between the geomembrane and underliner. This layer may not be filled by tailings during initial deposition when pore pressures are small. This zone would need to be filled with eroded materials before a stable condition can be reached. The area of the zone would depend on the intimacy of the contact between the geomembrane and underliner.

- Erosion of tailings may be stress dependent. Wong et al. (2008) found that the compressibility index of non-segregating tailings containing 21% fines can differ by three orders of magnitude with stresses ranging from 1-2 kPa to 250-400 kPa. They postulated that the high compressibility at low stresses was due to lack of a sand soil skeleton, which only formed at higher stresses. Similar behavior could govern erosion. However, the behavior could change again at higher stresses. Tomlinson and Vaid (2000) found that higher confining stresses make uniform sands more susceptible to erosion. The effect of stress on piping erosion is an ongoing research topic.

Test materials and method

The tailing examined was a mixture of cycloned tailings from a copper-molybdenum mine in British Columbia (Canada). They can be classified as a silty sand (USCS classification system). The gradation is shown in Figure 8. The material had a fines tail that makes the material borderline potentially suffusive (as assessed using Kenny and Lau 1985a; Wan and Fell 2008; Moraci et al. 2014; see Supplementary material for more details).

The tailings examined in this study were prepared by mixing with potable water from the city of Kingston to approximately 60% solids (67% moisture content), and carefully poured over the geomembrane with a defect until the slurry level reached a thickness of approximately 30 cm (dry density of 0.9 g/cm^3). The tailings were allowed to settle and segregate to simulate sub-aqueous deposition. Clear supernatant water was removed and the final tailings thickness was approximately 22 cm with dry density of $1.1\text{-}1.2 \text{ g/cm}^3$. In the field, tailings may be eroded and subjected to drying and wetting cycles. This study assumes the tailings in contact with the liner had remained relatively saturated throughout the operating life of the storage facility. Assuming 100% saturation and a specific gravity of 2.7, the porosity of the tailings is estimated to be between 65% and 73%. Rowe et al. (2016) reported a hydraulic conductivity of the tailings of between $1 \times 10^{-7} \text{ m/a}$ at 1500 kPa and $5 \times 10^{-7} \text{ m/s}$ at 50 kPa.

Three underliner materials (with grading curves identified as Test 1, 2, and 3 in Figure 8 and shown in Figure 9) not satisfying the “no-erosion” criteria proposed by Foster and Fell (2001) were studied. According Foster and Fell’s proposed continuing erosion boundary, all three materials should not continuously erode, although the grading curve referred to as Test 3 is very close to their proposed boundary. The materials were all angular to sub-angular gravel sourced from quarries near Kingston, Ontario, and each had a coefficient of uniformity of four ($C_u=4$). The underliner material was placed in two 10 cm lifts (total thickness of 20 cm), mixed and lightly tamped with a hammer to produce as flat a surface as possible (to simulate proof rolling). The dry density of the as-placed material varied from 1720 to 1800 kg/m³. Since no vibration was employed for compaction, the relative density is likely low. Low relative density results in large void constrictions that likely present a worst case for erosion (Indraratna et al. 2007). An example of the prepared surface for each underliner is shown in Figure 9.

Considering the particles size and void size located at the surface in Figure 9, it can be inferred that, depending on where the 1 cm diameter defect is located, the constriction size encountered along the flow path may be different. Thus, varying amounts of erosion may be expected for nominally the same test material due to probability of different constriction paths being, or not being, present below and leading away from the defect. For this reason, triplicate tests were performed for both Test configurations #1 and #2 underliners and duplicate tests were conducted for the Test configuration #3 underliner (this test configuration was likely above the limits of what is permitted based on consideration of factors other than erosion (e.g., puncturing and installation damage)). Post-test gradation analysis were undertaken to assess the in-situ underliner in the region of the hole (discussed in results and discussion.)

The geomembrane was a 1 mm-thick linear low density polyethylene (LLDPE) manufactured to conform to GRI-GM17 (GRI, 2015). A 1 cm-diameter hole was located at the centre. A geocomposite drain (GCD), comprised of a geonet sandwiched by 2 layers of geotextile, was placed at the bottom of the cell to provide filtration and a high transmissivity drain. Two layers of GCD, used to provide both separation and a plane to allow water to form uniform pore pressure, were placed between the tailings and a sand leveling layer. Above the GCD, the sand levelling layer (wrapped in a separator geotextile) protected the rubber bladder onto which the total stress (air pressure) was applied.

Stress path and loading procedure

After the materials were placed, they were subjected to a vertical loading path simulating deposition of overlying tailings as in a TSF. The loading stages are summarized in Table 3.

The stresses indicated in Table 3 were applied above the tailings in the cell (Figure 6) to simulate the weight of overlying tailings and its associated hydrostatic head. Stages 1-3 represent three different overlying tailings thicknesses, each with two heads to assess the effect of pond level at the same effective vertical stress (i.e., similar void ratio). The total stresses are estimated based on an assumed average tailings unit weight of 16 kN/m³.

With each stage, the vertical total stress, σ_v , was increased with an accompanying increase in pore pressure, u , in the tailings. The pore pressure away from the top boundary then decreases to an equilibrium values with consolidation of the tailings. The pore pressure at the top of the tailings was continuously adjusted to desired values using a regulator to maintain the equilibrium pore pressure distribution in the tailings.

The loading path and material placement simulated in this test program are representative of the common practice of hydraulically deposited tailings. The stress conditions associated with

filtered tailings (or “dry stacking”) storage is expected to be much more favourable than those examined in this study. Thus, this study should provide a conservative indication of performance for dry stacking scenarios.

Results and discussion

The leakage results are presented in Table 4. For Test 3A, there was evidence of side wall leakage and a puncture due to underlying gravel upon exhumation (after Stage 4). It is not clear exactly when the puncture and sidewall leakage took place; however, since the leakage rates prior to Stage 4 appeared consistent with the other tests, it is considered probable that both sidewall leakage and puncture occurred during Stage 4. Due to the presence of additional defects (from a puncture in the geomembrane and side-wall leakage), a smaller hydraulic gradient likely existed at the central 1 cm-defect for Test 3A. Thus, it is difficult to directly compare the test with the others. However, the results of Test 3A are still informative as it conforms to the general trend observed in Test 1 and 2. Although the leakage results did not suggest the much coarser Test 3 underliner was more prone to continuous erosion for stresses prior to Stage 4, it showed that the underliner may cause punctures and excessive strains in the geomembrane which can significantly impact short-term and long-term performance respectively. In a separate test performed on Test 3 underliner (Test 3B), strains (measured and calculated per Tognon et al. 2000) in excess of 25% were observed with 70 kPa of total stress. In this test, a stable leakage rate was obtained in Stage 1a and 1. However, upon exhumation after Stage 1, a piece of foreign material was found in the tailings directly above the defect. Thus, the stable result could not be confirmed for Stage 1.

Erosion at low stresses

Test 1A, 2B, and 3A showed similar leakage patterns under low stress conditions despite different underliner gradations. All three tests can be characterized by an initially stable condition at Stage 1a, followed by an unstable Stage 1 (with the increase in head on the tailings), and a stable Stage 2a (with simulated placement of more tailings). The leakage rates for the three tests are plotted in Figure 10.

The leakage results suggest that for a filter-incompatible subgrade at relatively low stresses (or early stages of tailings deposition), tailings migration, is to some degree, not as dependent on the underliner gradation as on small changes in pore pressure and effective stress. Such stress changes appeared to govern tailings migration through the defect. When the tailings were only subjected to a small effective stress, an increase in pore pressure facilitated movement. However, under the same pore pressure, when the tailings had been subject to a slight larger effective stress (30 kPa), movement was significantly hindered. This point is further suggested by Test 2C, where 60 kPa of effective stress was induced prior to loading to Stage 1; in this case, the leakage rate was stable for approximately 1.5 hours at 70 L/day. Subsequent stages produced stable and low leakage results similar to those found in Rowe et al. (2016) with a filter-compatible subgrade.

During the unstable Stage 1 loading periods (Tests 1A, 2B, and 3) leakage was typically characterized by sudden increases (i.e., by more than double the previous leakage), followed by relatively stable periods where the leakage could decrease to values comparable or smaller than in Stage 1a and 2a. However, the relatively stable periods in Stage 1 never met the stability criteria prior to another increase in leakage rate. The sudden nature of piping erosion was also

observed by Moffat and Fannin (2011) in their studies of internal erodibility of gravels and silty sands.

After unstable Stage 1 conditions (i.e., in Tests 1A, 2A, 2B, and 3A), the tailings surface was exposed for inspection prior to filling and leveling off the surface with new tailings for the next stage (when applicable). Removal of the GCD above the tailings revealed a surface erosion feature in all these test configurations (Test 1A, 2B, 3A shown in Figure 11). These erosion features were located at the centre the cell, approximately above the geomembrane defect. These distinct erosion features were not observed at the following stages where leakage became stable, or in the stable tests (Tests 1B, 1C, 2C) at the times the surface was exposed viz:

- Test 1A - Stage 2a, 3, 4
- Test 1B - Stage 1
- Test 1C – Stage 1, 4
- Test 2B - Stage 2a, 2, 4
- Test 2C – Stage 4
- Test 3A – Stage 2a, 2
- Test 3B – Stage 1a

Thus, the erosion feature can be correlated to the unstable leakage that was observed to only occur during Stage 1.

For Test 1A, 2A, and 2B which showed a surface erosion feature and unstable leakage readings in Stage 1, further evidence of erosion was observed when the tailings were exhumed after the final loading stage. Similar features were not observed in tests that were stable during Stage 1 (Test 1B and 2C). For tests that had the surface erosion feature, erosion features encountered during in exhumation are generally illustrated in Figure 12. In particular, erosion features encountered near the geomembrane defect for Test 2A and Test 1A are presented in Figure 13. The Test 2A features were observed immediately after the unstable condition at Stage 1 (higher loads were not imposed prior to exhumation), whereas the Test 1A features were

observed after stable conditions at Stage 4 (subsequent to initially unstable conditions at Stage 1). Because no surface erosion features were observed for post-Stage 1 loads in Test 1A, this finding suggests that the features were likely created during the unstable Stage 1. Test 2A verifies that these features can form during Stage 1.

The leakage results and visual findings showed that the tailings tested were subjected to erosion under Stage 1 conditions for all three subgrades examined (Test 1C did not meet the unstable criteria at Stage 1 but the high steady leakage rate compared to Stage 1a and 2a suggests erosion occurred.) However, subsequent steady leakage rates suggested that erosion likely did not continue at subsequent higher stresses, even though the tailings (especially near the defect) still contained open voids (e.g., as seen for Test 1A; Figure 13b). In other words, if voids form near defects under low effective stresses, they likely remain arched open under higher stresses for the type of tailings tested in this study. This erosion phenomenon explains why the resulting leakage rates found in this study were at least an order of magnitude higher than those observed by Rowe et al. (2016).

Other Effects on Erosion Voids

In the field, the basal layers of tailings as tested in the GLLS are overlain by more tailings. Thus, it can be postulated that the voids formed during early deposition phases may progressively be filled with tailings from newly deposited layers, provided a stable condition is reached near the defect (i.e., the leakage rate would reduce over time). The tests performed in this study could only simulate this environment to a limited extent due to the following:

- No unstable Stage 1 condition was held longer than 24 hours
- No new tailings slurry was placed during unstable Stage 1 conditions
- Only 2-3 cm of new tailings slurry was placed after unstable Stage 1 conditions

The test duration for Tests 1A and 2B were extended after stable results were obtained in Stage 4 to assess possible change in leakage over time (Figure 14). Stable conditions (3 hours or more of pressurization at approximately $\sigma_v = 530$ kPa, $u = 350$ kPa during which hourly leakage did not vary by more than 15%) were achieved for Test 1A between 4-8 hours and Test 2B between 1-5 hours. There appears to be a slight trend of reducing flow rate over time. It is postulated that this is the result of migrating suffusive fines as previously observed by Rowe et al. (2016). Gradation samples taken near the hole could not provide a resolution fine enough to identify this movement.

Also plotted on Figure 14 is the leakage rate for Test 1C-Stage 4, which met the definition of being a stable test. However, it also likely experienced some erosion due to the high leakage rate. The test is an example of how off-and-on spigot rotation at a TSF could influence the leakage rate. It was often observed that when pressure was re-introduced after depressurization (e.g., an overnight stoppage), the leakage after re-pressurization was usually more than 15% different from the previous test. For Test 1C, even though there was stable flow between 8 to 12 hours at around 200 L/day (meeting stability criteria), subsequent re-pressurization increased the leakage rate to over 1000 L/day. The sudden nature of this increase is similar to that observed during unstable Stage 1 conditions. This behavior implies that sudden pressurization could destroy the pseudo-stable structure that existed previously under relatively stable conditions. This is consistent with findings from Tomlinson and Vaid (2000), who observed a significant decrease in the critical mobilization hydraulic gradient required to cause piping when the rate of inducing the gradient was increased. Richards and Reddy (2010) also had similar findings. It is unclear if rotational spigot operation at a TSF could induce such sudden gradients, but as thicker layers of tailings are deposited above the layer in contact with the geomembrane defect, it can be expected

that the induced gradients will become less sudden. Thus, the behavior is likely magnified in our study (i.e., our study is likely conservative and overestimates the susceptibility to piping due to sudden re-pressurization); this warrants more investigation.

Quality of Contact

Upon exhumation of the geomembrane and defect, migrated tailings at the surface of the underliner appeared to form a filter cake (Figure 15 shows examples of this for Test 1 underliner).

Two pieces of evidence in the exhumed underliners suggest that the quality of contact between the geomembrane and underliner is a governing factor in stability for the low-stress erosion phenomenon observed:

1. More migration occurred laterally (typically up to 20 cm) than vertically (typically 4-6 cm based on sieve analysis of samples in the footprint).
2. Smaller footprints are consistently observed for more stable tests.

It has been well established that good contact (low transmissivity) between the liner and subgrade is key to low leakage through composite liner systems (Rowe, 2012). The quality of this contact depends on the geomembrane type, subgrade condition, and construction practices. Thus, it is not a surprise that the same concept may govern tailings migration due to leakage.

In cases where good contact exists, lateral migration of tailings is limited by the connected voids in the underliner material. Thus, the tailings only fill up this limiting volume. If the underliner voids that were filled by tailings do not continuously erode (underliner gradation and hydraulic gradient dependent), a steady leakage rate results. When contact is poor, the tailings can more readily migrate laterally at the underliner-geomembrane interface and hence have access to far more voids in the underliner, prior to the underliner gradation having any effect on

stability. The continuous filling of tailings (via erosion from above) into the open space was likely what we observed during Stage 1 because the phenomenon did not appear to be significantly dependent on the underliner gradation.

The presence of what appears to be erosion features on the filter cake in Test 2B (Figure 16) suggest the full area of the observed filter cake footprint was not flowing under stable conditions. Thus, it is hypothesized that the filter cake footprint observed likely formed under low stresses (i.e., during initial placement of tailings or Stage 1). As the total stress increased, the effective flowing footprint may have reduced (better contact was achieved), causing the void footprint required to be filled up to be reduced. This is a possible explanation for why stability was observed at larger total stresses.

Another hypothesized reason for stability was the increase in effective stress. It is postulated that in Stage 1a and 1, the tailings above the defect was still slurry-like and lacked an interlocking frictional sand-to-sand skeleton that would “lock in” particles (similar to Stage I of the Mechanistic Model proposed by Wong et al. 2008). In other words, the tailings were more mobile (has a lower rheological yield stress) at these stages, and therefore more readily moved through the defect into the geomembrane-underliner interface. Once a small effective stress was established, a soil skeleton formed, and it became more difficult for tailings particles to mobilize. However, at least for some underliner gradations and density, this effect may diminish at larger effective stresses, since Tomlinson and Vaid (2000) found that loose, uniform sands eroded more easily (at a lower hydraulic gradient) with larger confining stress in the range of 50-300 kPa.

Analysis of “Filter Cake”

The footprints of filter cakes (examples are shown on Figure 15) from all tests except 2C and 3B were excavated at intervals (e.g., 0-2 cm; 2-4 cm except for test 3A where intervals were 0-5cm

and 5-10 cm), and the gap-graded material at each internal was sieved to assess the extent of the tailings penetration at the end of the test. From the gradation results for all tests (Supplemental material), the following observations were made regarding tailings migration:

- little to no tailings were observed past 4-6 cm depth (with the exception of Test 3A where tailings were observed past 10 cm);
- more tailings were present closer to the surface of the underliner than at depth; and
- the tailings were coarser closer to the surface of the underliner than at depth.

These observations are consistent with the numerical model predictions (presented earlier), in that the hydraulic gradient (therefore seepage velocity) likely became smaller further away from the defect in the underliner. The presence of fewer and finer particles away from the defect suggests the hydrodynamic conditions (as per Kenny et al. 1985b) required to transport eroded tailings particles likely diminished away from the defect. This would result in the deposition of particles, starting with the largest near the defect, to the finest away from the defect. In turn, these deposited particles (if not eroded further), reduced the constriction sizes near the defect, and allowed for eventual filtration. This process provides a possible explanation for why filtration occurs on materials that require some amount of erosion prior to successful filtration (as observed by Foster and Fell 2001). A comparison between data compiled by Foster and Fell can be made with the gap-graded materials taken from the filter-cake zone below the geomembrane to assess whether their proposed continuing erosion boundary gives conservative predictions for the case with geomembrane defects. The Foster and Fell (2001) boundary was estimated based on traditional filtration tests and for a different test set up than that examined here. In addition to differences discussed in the Apparatus section, traditional tests use filters that likely have higher relative densities than underliners from this study. Hence, stable results observed by Foster and

Fell might not be stable with a more poorly compacted filter (as was the underliner from this study).

Furthermore, Foster and Fell used representative base and filters gradations data in their analysis. This is in contrast with our gap-graded underliner sample, which is a potentially suffusive material that contains tailings within the skeleton of the underliner. Although other methods exist to assess suffusion (as used to analyze the tailings in the Apparatus section), the fact that the filter cake-underliner mixture was gap-graded allowed the material to be easily split into a coarse and fine fraction. The split materials could then be assessed as separate materials using retention criteria (as advocated by others including Kezdi 1969; Sherard 1979; and DeMello 1975).

Figure 17 shows the underliner gradation data from this study superimposed on the “no seal” tests and Foster and Fell’s erosion boundaries (extracted from Figure 6 of Foster and Fell 2001). The “no seal” test results suggest that when almost all of the base material is smaller than a ninth of the d_{15} of the filter, erosion appeared to be continuous. Foster and Fell identified the continuous erosion cut-off percentage of the base to be 95% (i.e., when greater than 95% of the base is smaller than the d_{15} of the filter, they predict the base will continuously eroded through the filter.) The results from this study are in general agreement with those presented by Foster and Fell because stable conditions were eventually reached (after varying degrees of erosion) in all Test 1 and 2 underliners. Test 3A was difficult to interpret as the intermittent turbid outflow suggests continuous erosion, but stable conditions were reached in several stages. As observed in Test 3A (and a few tests considered by Foster and Fell and presented in Figure 17), materials near the excessive erosion boundary are potentially continuously erodible. That said, if only Stage 1 was considered for all tests, then Test 1A, 2A, 2B, and 3 could all have been interpreted

to be continuously eroding. This low stress erosion phenomenon cannot be predicted using Foster and Fell (2001) and is likely unique to the geomembrane defect scenario. This phenomenon is likely more closely associated with the contact conditions between the geomembrane and the underliners, rather than filter compatibility between the tailings and underliner.

Summary and Conclusions

This study examined the conditions under which erosion of silty sand tailings might be expected through a 1 cm-diameter geomembrane defect over three different graded underliners where the tailings and underliner are filter incompatible.

It is shown that the geomembrane defect introduces a preferential location for pore pressure dissipation. Based on an axisymmetric, steady-state seepage model, a 10 mm-diameter hole gives rise to large hydraulic gradients in the tailings above the hole and low hydraulic gradients away from the hole in a permeable underliner.

For the filter incompatible conditions examined, it is concluded that:

- Both the hydraulic gradient (resulting from pore pressure) and effective stress influenced tailings erosion through the geomembrane defect.
- When silty sand tailings and the underliner are filter incompatible (DF15/DB85 of 5.5 to 13.5), some erosion can be expected to occur under low stresses (early phases of hydraulic deposition). This erosion does not appear to be significantly dependent on the DF15/DB85 ratio.
- Erosion appears to be significantly hindered once 30-60kPa of vertical effective stress was present, and remained so up to pore pressure of 350 kPa (with exception to the DF15/DB85=13.5 underliner, which was relatively stable up to 200 kPa of pore pressure).

- If migration occurs during low stress levels, voids (barely noticeable to the naked eye) may form in the silty sand tailings to allow much higher leakage rates than previously suggested when the tailings and underliner were filter compatible (Rowe et al. 2016; Joshi et al. 2016), even if no additional migration occurs at higher stress levels. More work is needed to assess if leakage rates reduce over time.
- Poor geomembrane and subgrade contact likely facilitate migration of tailings, especially under low stresses. Factors leading to poor contact should be minimized to minimize tailings migration and possible increases to maximum allowable leakage.
- The Foster and Fell (2001) approach for assessing successful filtration after an amount of erosion provided a reasonable approach for predicting continuous erosion when a geomembrane defect exists between two materials at vertical effective stresses greater than 30 kPa. Below 30 kPa, the approach will likely result in false prediction of stability because it does not consider the geomembrane-underliner interface.

When considering the work presented in this paper it is cautioned that neither the tests conducted in this study or those considered by Foster and Fell (2001) involved pore pressure exceeding 300-400 kPa. Should seepage velocity be governing stability, it can be expected that the boundaries would shift lower at larger pore pressures which may be encountered in some TSFs. Moreover, readers are cautioned that erosion behavior may not be the same for different types of tailings (as no-erosion criteria vary depending on the percentage of fines of the base material).

Acknowledgements

This work was funded by the Natural Sciences and Engineering Research Council of Canada through a Collaborative Research and Development Grants in partnership with Klohn Crippen Berger Ltd. The value of discussions and the assistance and advice of Mr. Harvey McLeod is very gratefully acknowledged. The apparatus was developed with funding from the Canada Foundation for Innovation and the Ontario Government.

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Figure Captions

Figure 1. Use of geomembrane at the base and upstream face of a TSF

Figure 2. Illustration of flow through a geomembrane defect at a lined-TSF (arrows show conceptual direction of seepage)

Figure 3. Photo of erosion void in exhumed silty sand tailings (Courtesy of Dr. P. Joshi).

Figure 4. Estimated pore pressure contours (2 m contour interval) above the geomembrane with 10 mm dia. defect.

Figure 5. Estimated pore pressure contours (0.001 m contour interval) below the geomembrane.

Figure 6. Schematic of modified GLLS used in this study.

Figure 7. Sketch of the NEF (a) and slurry (b) test apparatus (as described in Sherard and Dunnigan, 1984;1989)

Figure 8. Tailings and underliner gradations.

Figure 9. Typical underliner surface for Test configuration #1 (a), #2 (b), and #3 (c)

Figure 10. Leakage rate during permeation for Test 1A, 2B, and 3A at Stage 1a (a), Stage 1 (b), Stage 2a (c).

Figure 11. Tailings surface of unstable tests: (a) Test 1A, (b) Test 2B, (c) Test 3A.

Figure 12. (a) Generalized erosion and deposition features discovered during exhumation of unstable tests (after final loading stage), (b) blow-up of insert in (a)

Figure 13. Open voids directly above 10 mm defect Test 2A (a); Test 1A (b)

Figure 14. Average leakage rates at Stage 4 for Test 1A, 1C, and 2B.

Figure 15. Underliner surface upon exhumation: (a) Test 1A- top left; (b) Test 1B-top right, (c) Test 1C – bottom

Figure 16. Open areas on the filter cake surface of the underliner in Test 2B

Figure 17. Split underliner data superimposed on “no seal” tests and erosion boundaries presented in Foster and Fell (2001)

Table 1. Input for illustrative Finite Element seepage model

Parameter	Tailings	Underliner
Saturated hydraulic conductivity (m/s)	10^{-7}	10^{-4}
Thickness (m)	0.3	0.3
Total head at boundary (m)	40 ¹	0.3 ²

Notes: 1. Boundary condition is at the top of the tailings
 2. Boundary condition is at the bottom of the underliner

Table 2. Comparison of Filtration Tests

Type of test	NEF	Slot	Slurry	GLLS
Reference	Sherard et al. (1989); Foster and Fell (2001)	Sherard et al. (1984)	Sherard et al. (1984)	this study
Flow orientation	Vertical	Horizontal	Vertical	Vertical
Pre-formed pipe geometry	1-2mm diameter	1.5 mm x 12.7 mm	None	None
Base placement	“compacted”	95% Standard Proctor	2.5x Liquid Limit	60% Solids
Water pressure applied at top of base (kPa)	413 kPa	390 kPa	390 kPa	Up to 400kPa

Table 3. Imposed stress path for testing program

Stage	Tailings Overburden (m)	Head (m)	σ_v^1 (kPa)	u^2 (kPa)	$\sigma_v'^3$ (kPa)
1a	1	3	36	30	6
1	1	6	66	60	6
2a	5	6	90	60	30
2	5	10	130	100	30
3a	15	16	250	160	90
3	15 ¹	20	290	200	90
4	30	35	530	350	180

- Notes:
- 1. Total stress applied at the top of the tailings, σ_v , did not exceed target values by more than 10 kPa.
 - 2. Pore pressure at top of tailings, u , did not exceed target values by more than 15 kPa, except for Stage 4 (max exceedance of 50 kPa)
 - 3. Vertical effective stress at top of the tailings, σ_v' , did not exceed target values by more than 10kPa, except for Test 2C (discussed in Results and discussion), and Stage 4 (maximum exceedance of 55 kPa)

Table 4. Stable leakage for each stage in each test conducted (in L/day)

Stage	Test 1A	Test 1B	Test1C	Test 2A	Test 2B	Test 2C ³	Test 3A	Test 3B
1a	100	10	80	-	20	-	40	10
1	U ¹	10	640	U ¹	U ¹	70 ⁴	U ^{1,5}	NA ⁷
2a	160	-	210	-	160	-	70	-
2	240	-	700	-	220	4	90	-
3a	280	-	760	-	280	-	110	-
3	370	-	970	-	590	4	550	-
4	340	-	200 ²	-	1040	4	NA ^{5,6}	-

- Notes:
1. U – indicates unstable (stable leakage rate could not be obtained)
 2. Stable leakage rate of Test 1C at stage 4 can be disrupted to 1,200 L/day by abrupt changes in gradient (i.e. turning inlet valve off and on)
 3. Test 2C was consolidated to $\sigma_v' = 60$ kPa (exceeds Stage 1 and 2 target σ_v') prior to running Stage 1.
 4. Leakage was only recorded for 1.5 hours for Stage 1 of Test 2C prior to inducing Stage 2.
 5. Outflow was observed to be intermittently turbid during test.
 6. Target pore pressure could not be maintained for more than 24 hours because the flow rate exceeded laboratory capacity of 2000 L/day after 10 hours.
 7. Test had stable leakage rate of approximately 50 L/day. However, exhumation after Stage 1 revealed a surface erosion feature similar to other unstable Stage 1 tests. Excavation near the defect revealed a foreign material had partially clogged the defect. Leakage rate at Stage 1a was determined to be stable because no erosion was observed at the surface (foreign material likely did not make its way to the hole at Stage 1a.)
 8. Leakage rates shown are accurate to $\pm 4\%$

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Figure 8. Tailings and underliner gradations.

Note: black and white blocks in scale reference is in centimetres.

Figure 9. Typical underliner surface for Test configuration #1 (a), #2 (b), and #3 (c)

Notes: 1. Larger symbols indicate a gap in permeation time occurred (typically shut down overnight) where the cell was depressurized and re-pressurized.
2. For Test 3A, the desired pore pressure could not be maintained after 6.5 hours into pressurization of Stage 1. A large erosion void was found upon exhumation as indicated in Figure 12.
3. The leakage rates are calculated using volumes collected from all 3 outlets as shown in Figure 6. This leakage does not equal the leakage exiting the defect during unsteady flow rates as the water level changes in the underliner.

Figure 10. Leakage rate during permeation for Test 1A, 2B, and 3A at Stage 1a (a), Stage 1 (b), Stage 2a (c).

Note: black and white scale reference is in centimetres.

Figure 11. Tailings surface of unstable tests: (a) Test 1A, (b) Test 2B, (c) Test 3A.

Note: 1. Newly deposited tailings not applicable for Test 2A.

2. Erosion features immediately above geomembrane defect was not obvious for Test 3A

3. Photo shown is taken from Test 2B.

4. Scale in photo is in centimetres.

Figure 12. (a) Generalized erosion and deposition features discovered during exhumation of unstable tests (after final loading stage), (b) blow-up of insert in (a)

Note: 1. Lines delineate a general difference in material colour/appearance directly above the hole and away from the hole. Circles identify open erosion features.
2. The triangular black object on the left side of the bottom photo is a masonry trowel pointing to the open erosion feature.

Figure 13. Open voids directly above 10 mm defect Test 2A (a); Test 1A (b)

Note: Red symbols indicate a gap in testing time occurred (typically shut down overnight) where the cell was depressurized and re-pressurized.

Figure 14. Average leakage rates at Stage 4 for Test 1A, 1C, and 2B.

Note: Black and white scale reference is in centimetres. The scale has a total length of 5cm.

Figure 15. Underliner surface upon exhumation: (a) Test 1A- top left; (b) Test 1B-top right, (c) Test 1C – bottom

Note: Black and white scale reference is in centimetres.

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