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EFFECTIVENESS OF GEOMEMBRANE LINERS IN MINIMIZING SEEPAGE IN TAILINGS STORAGE FACILITIES – NEW KNOWLEDGE*

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CANADA

SUMMARY

The new understandings from collaborative research programs between Klohn Crippen Berger Ltd and the Geo-Engineering Centre at Queen's University, Kingston, Ontario, provide a technical basis for quantifying leakage rates from tailings / geomembrane liner systems. The research program utilized hard rock copper tailings, which was screened to produce tailings with permeability in the range of 10^{-6} m/s to 10^{-9} m/s. Tailings were placed over a geomembrane, which had a hole varying from 1 mm to 10 mm in diameter, with a soil underliner of varying permeability. The samples were placed in a 590 mm diameter by 500 mm high rigid wall cell and subjected to a range of pressures up to 2000 kPa. A series of tests were out carried to assess the sensitivity of the leakage rate to: geomembrane type (LLDPE and HDPE); hole size; effect of wrinkles; effect of contact regularity; pressure; tailings permeability; underliner permeability; and, potential for piping.

The test results indicate that leakage from tailings / geomembrane liner systems is orders of magnitude less than leakage from typical landfill and heap leach geomembrane liner systems. The low leakage rate is due to the constraint

* *Efficacité des géomembranes pour minimiser l'exfiltration provenant des sites de résidus miniers - nouvelles connaissances*

of flow into a hole in the liner by the low permeability tailings. The rate of leakage is also non-linearly controlled by the permeability of the tailings and the head on the liner, but for many applications the leakage rate is on the order of 40 liters per day per hectare, assuming good quality control-quality assurance (QA-QC) and 10 mm diameter holes. The leakage rate reduced with the size of the hole, although with holes on the order of 1 mm, the leakage rate was not measurable.

Placement of tailings over wrinkles, which had a hole placed in the wrinkle, resulted in tailings infilling the folds of the liner and, therefore, limiting the effect leakage. Placement of pea gravel under the geomembrane resulted in piping of tailings through the hole indicating that control of the piping potential is required. Placement of a geotextile between the geomembrane and pea gravel controlled the piping. Further research is currently being carried out to understand the piping process, which currently suggests that although piping does occur, its extent may be limited by the reduction in flow through the hole and local "plugging" of the pea gravel.

The research confirms that the practice, in many jurisdictions, of requiring a "drainage" layer over the liner, with the objective of reducing the head on the liner, is counterproductive in that it provides a path for leakage from the overlying consolidating tailings. This observation, combined with the practical observation that most holes in liners are produced during placement of an overlying drainage or "protective" layer, confirms the best practice approach is to ensure that tailings is placed directly overly the geomembrane liner. The effect of various levels of quality control-quality assurance is to increase the number of holes and therefore the leakage rate. In tailings facilities, the allowable leakage rate is typically determined on the basis of contaminant sources, contaminant transport and environmental effect on the receiving environment. Optimization of liner placement, particularly in difficult physical settings, should balance site preparation and QA-QC with a suitable factor of safety against the allowable leakage rate.

Geomembrane liners can provide a significant barrier to leakage from tailings facilities and ongoing research will continue to improve our understanding. In addition to the current research on piping, future research programs will assess the effects of aging on geomembrane liners. For example: current research indicates that geomembrane aging is significantly reduced when the temperature is consistent, such as in the base of a tailings facility; additionally, optimization of the materiasl and oxidants that are used to manufacture the liner can increase the liner life and is a practical research objective. Klohn Crippen Berger Ltd. and the Geo-Engineering Center at Queens University continue to collaborate on research opportunities to improve the understanding of the role of geomembrane liners in tailings storage facilities.

Practical implications of the research program in designing of modern TSFs were discussed.

Keywords: Laboratory test, leakage, geotextile, piping, synthetic material, tailings dam.

RÉSUMÉ

Les nouvelles connaissances obtenues à partir des programmes de recherche conjointe entre Klohn Crippen Berger Ltd et le Geo-Engineering Centre de l'Université Queen's à Kingston, en Ontario, fournissent une référence technique pour quantifier les débits de fuite provenant de systèmes formés de géomembranes et de résidus miniers. Le programme de recherche a utilisé des stériles de cuivre issus d'une roche dure ; ils ont été tamisés pour produire des résidus dont la perméabilité est comprise entre 10^{-6} m/s et 10^{-9} m/s. Ils ont été placés sur une géomembrane perforée par des trous variant entre 1 mm et 10 mm de diamètre, reposant sur une sous-couche de sol avec une perméabilité variable. Les échantillons ont été confinés dans une cellule à paroi rigide de 590 mm de diamètre sur 500 mm de hauteur, soumise à une gamme de pressions allant jusqu'à 2000 kPa. Une série d'essais ont été effectués pour évaluer la sensibilité du débit de fuite: type de géomembrane (LLDPE et HDPE); taille du trou; effet des plis; effet de l'uniformité du contact; pression; perméabilité des résidus; perméabilité de la sous-couche; potentiel de migration des particules fines.

Les résultats des essais indiquent que les fuites provenant des systèmes de résidus sur géomembrane sont de plusieurs ordres de grandeur inférieurs à ceux issus des membranes utilisées dans des décharges municipales ou dans la technique de lixiviation en tas. Le faible débit de fuite est dû à la diminution de l'écoulement causée par la faible perméabilité des résidus avoisinants les défauts de la membrane. Le débit de fuite est également contrôlé de manière non linéaire par la perméabilité des résidus et par la charge hydraulique sur la membrane. Pour de nombreux cas, le débit de fuite est de l'ordre de 40 litres par jour par hectare. Cette quantité suppose de bons programmes d'assurance et de contrôle de la qualité ainsi que des trous de 10 mm de diamètre. Le débit de fuite diminue avec la taille des trous, mais lorsqu'ils atteignent environ 1 mm, le débit n'est plus mesurable.

La mise en place de résidus sur des plis de la géomembrane renfermant des trous a entraîné le remplissage de ces plis par des résidus ; ceci a eu pour effet de diminuer les fuites. La présence de gravier fin sous la géomembrane a entraîné un effet de renard dans les résidus, à travers les trous ; ceci indique qu'un contrôle du potentiel de migration des fines est requis. La mise en place d'un géotextile entre la géomembrane et le gravier fin a contrôlé la migration des fines. D'autres recherches sont en cours pour comprendre ce processus de migration. Bien que ce mécanisme puisse exister, celles-ci suggèrent actuellement que son ampleur peut être limitée par la réduction du débit à travers les trous par les résidus et par le colmatage local du gravier fin.

Exigée dans de nombreuses juridictions, une couche de drainage peut être posée sur la membrane dans le but de réduire la charge hydraulique sur le revêtement. La recherche confirme que cette pratique est contre-productive puisqu'elle constitue un chemin de percolation pour l'eau provenant de la consolidation des résidus sus-jacents. Il est observé sur le terrain que la plupart des trous dans les membranes sont produits pendant la mise en place de cette couche de drainage ou couche protectrice. Cette constatation confirme que la meilleure pratique consiste à s'assurer que les résidus soient placés directement par-dessus la géomembrane. L'effet des différents niveaux d'assurance et de contrôle de la qualité est paradoxalement d'augmenter le nombre de trous et, donc, le débit de fuite. Pour les sites de résidus miniers, le débit de fuite admissible est habituellement déterminé en fonction des sources de contaminants, du transport de ces derniers et de l'effet environnemental sur le milieu récepteur. L'optimisation de la mise en place de la membrane, en particulier dans des contextes physiques difficiles, doit équilibrer la préparation du site et son contrôle de qualité avec un facteur de sécurité approprié par rapport aux débits de fuite admissibles.

Les géomembranes peuvent constituer une barrière importante pour contrôler les fuites provenant des sites contenant des résidus miniers. Les études en cours continueront d'en améliorer notre compréhension. En plus de la recherche actuelle sur la migration des particules fines, de futures investigations évalueront les effets du vieillissement sur les géomembranes. Par exemple, les recherches récentes indiquent que la dégradation de la géomembrane est considérablement réduite lorsque sa température est constante, comme dans la portion inférieure d'un parc de résidus miniers. De plus, c'est un objectif réaliste de viser à des améliorations dans la construction des membranes, ceci pouvant également augmenter leur durée de vie. Klohn Crippen Berger Ltd. et le Geo-Engineering Centre de l'Université Queens continuent de collaborer à des recherches afin d'améliorer la compréhension du rôle des géomembranes dans les sites de stockage des résidus miniers.

Les implications pratiques de ce programme de recherche pour la conception de sites modernes contenant des stériles miniers ont été discutées.

Mots-clés: Barrages de stériles, essai de laboratoire, fuite, géotextile, matériau synthétique, renard.

1. INTRODUCTION

Geomembranes are factory-manufactured, flexible, relatively impermeable thin plastic sheets installed as a liquid and/or vapour barrier. Geomembranes are designed to serve in a variety of containment situations: to contain fresh water, contact water, process fluids, leachate, mine liquors, and other effluents that cannot be disposed as is into the environment; to minimize seepage into the surrounding environment; and for the protection of ground and surface water. The use of geomembrane liners is common in landfills and, more recently, heap leach applications. A considerable amount of research has been, and continues to be, carried out to better understand the properties and performance of liner systems in these applications. The use of geomembranes for containment of mine tailings, however, has only been applied in some regulatory jurisdictions and typically for cyanide gold tailing storage facilities.

Facilities such as heap leach pads and fresh water storage ponds have economic benefits in adopting geomembrane as a primary liner material (limiting water or mineral solution loss). For most other facilities the driving, regulated or voluntary, motivation is in limiting environmental contamination. With the growing interest of environmental agencies and industries in pollution reduction and the added direct/indirect economic advantages, there has been an increasing trend in the use of geomembranes in recent years in Canada and internationally. Despite that, the use of geomembranes in tailings storage facilities (TSFs) is not universally accepted, partly due to cost and partly due to the paucity of data on its performance in tailings containment.

The most common geomembranes in mining facilities include: high-density polyethylene (HDPE), linear low-density polyethylene (LLDPE), PVC, and elastomeric (e.g., Bituminous) geomembranes. The research work discussed in this paper focuses on the performance of polymeric geomembranes (HDPE and LLDPE) due to: (i) the vulnerability of the thin polymeric material to damage both during installation and throughout the service life; and (ii) difficulty to achieve continuous close contact between the lighter geomembranes and the foundation either because the geomembrane will expand and form wrinkles when heated upon exposure to solar radiation or deform during placement of overlying materials.

Good quality control (QC) and quality assurance (QA) is a standard practice during field installation of geomembranes. However it is practically impossible to obtain a zero-leak installation. Any damage (tears and punctures) may compromise the effectiveness of the geomembrane as a containment barrier and result in contaminant release into the environment. Geomembrane holes may be introduced in the short-term (e.g., during construction) or in the long-term (e.g., due to the sustained strain on the geomembrane due to a poorly graded coarse foundation or due to the folds introduced while the liner is being covered). Giroud and Bonaparte [1], [2] recommended that a geomembrane installed with good construction QA-QC on a well-prepared foundation should be assumed to have 2.5 to 5 holes per hectare. The recommendation is generally found to be valid for landfills where a high level of QA-QC is typically exercised. A poor QA-QC construction procedure could have on the order of 26 holes per hectare as estimated [3]. TSFs often face challenges due to their large areas, variable topography and variable foundation conditions. These unique situations may potentially increase the number of defects.

Wrinkles (sometimes called waves) are formed due to the thermal expansion of the geomembrane. Several laboratory and field studies [4], [5], [6] have reported that wrinkles reduce in size when covered but do not go away even under an applied vertical stress of up to 3000 kPa. Networks of wrinkles may become conduits which allow fluid access to holes, resulting in higher leakage into the foundation [7]. In the long term, concentrated strains along the bends caused by the wrinkle deformation can result in stress cracking of the geomembrane and further increase in leakage.

2. KNOWN UNKNOWNS

The design basis and performance prediction for liners used to contain tailings is usually based on the results of liners research for landfills. However, there are significant differences between landfills and TSFs, as seen in Fig. 1. Presently, these differences generally are not being correctly considered in the design of lined tailings facilities. In addition, there are unique properties of the geomembrane/tailings systems which have not been adequately researched or quantified. Some examples of the significant differences between geomembrane/tailings systems versus geomembrane/landfill systems are: 1) tailings are typically of low hydraulic conductivity and might be expected to provide higher resistance to leakage through the geomembrane than that provided by the drainage system above the liner in landfill applications (which is expected to reduce the leakage); 2) tailings dam applications may have much higher heads acting on the geomembrane than in landfill systems (which may increase the leakage); and, 3) tailings are fine-grained thus may have migration of fines through the geomembrane holes or piping of the tailings through a hole in a geomembrane wrinkle with a potential for infilling wrinkles (which may reduce their hydraulic significance).

Leakage through a geomembrane defect depends on: 1) the number and size of holes; 2) the thickness and hydraulic conductivity of soils in contact with

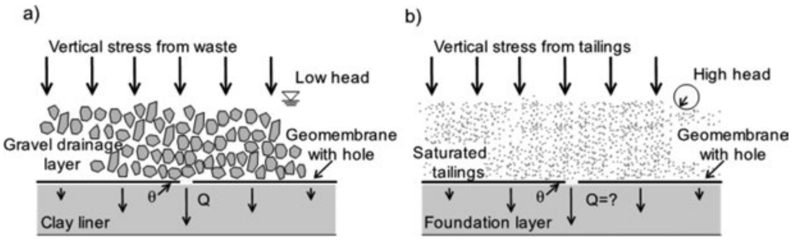

Fig. 1
Cross-section showing: (a) Geomembrane hole in a typical municipal solid waste landfill configuration, and (b) Geomembrane hole in a mine tailings containment configuration.
Coupe transversale montrant : (a) géomembrane perforée dans une configuration typique de décharge municipale pour déchets solides
(b) géomembrane perforée dans une configuration de confinement de résidus miniers.

the geomembrane; 3) the stresses acting on the liner; 4) the hydraulic gradient across the liner; and, 4) the transmissivity at the interface between geomembrane and adjacent soils [8], [9]. Leakage through holes in a geomembrane in a landfill or heap leach application is well understood. In those applications, generally a much higher permeability soil (for drainage purpose) overlies the geomembrane resting on an underliner (foundation) with very low permeability. With a reversed configuration in TSFs, i.e., with a lower permeability tailings overlying the geomembrane, the leakage through geomembrane defects had not been historically well quantified.

Some work has been done for the case of a permeable soil above and below a geomembrane with defects [10], [11], [12], [13]. However, the proposed empirical relations and mathematical models have severe limitations and can only be used for situations that do not necessarily represent tailings facilities. Although finite element seepage models, such as SEEP/W, have been adopted in simulating these cases, there is no basis to verify model assumptions and there is little specific data to permit their rational design and long-term assessment.

3. RESEARCH COLLABORATION

Recognizing the gaps in understanding leakage through geomembrane holes in a TSF application, Klohn Crippen Berger Ltd. initiated a research program and partnered with the Geo-Engineering Centre at Queen's University to: 1) conduct unique large-scale experiments with specialized equipment to quantify leakage through holes in the geomembrane using real materials (tailings) under realistic physical conditions; 2) establish a technical basis for design of geomembrane lined tailing management systems to minimize fluid leakage into the surrounding environment; 3) transfer the new knowledge acquired through the research regarding the factors affecting leakage and appropriate techniques to predict leakage to a broader geotechnical consulting industry and to better manage seepage containment of mining generated wastes; and, 4) share the vision of constructing geomembrane lined tailing management systems that provide more effective and reliable environmental protection. The results of the research are described in more detail in associated publications [14], [15], [16].

4. RESEARCH PROGRAM AND SUMMARY OF THE FINDINGS

4.1. Research program

The properties of the tailings and underliners used in the study are summarized in Table 1. The tailings were sourced from a hard rock copper tailings, which was screened to generate a range of potential permeabilities (k). Four geomembranes, 1 mm and 2 mm thick HDPE and LLDPE were used in the study. A 4 mm thick nonwoven, needle-punched geotextile with mass per unit area of 580 g/m^2 that meets the filtration criteria with all tailings was used in some tests. Refer to [16] and [17] for additional details on the materials.

All tests were conducted in a 590 mm-diameter, 500 mm-high rigid test cell (Fig. 2). In a typical test, a 0.14 m thick layer of underliner was compacted to an initial dry density of 16.5 kN/m^3 to 17 kN/m^3 at 10.5% to 11% gravimetric water content and then uniformly saturated from a layer of geocomposite drain below. A geomembrane specimen with a central circular defect (1.5 mm, 10 mm, or 20 mm in diameter) or with a 60 mm x 200 mm wide wrinkle with or without a 10 mm diameter hole was then installed on top and a perimeter seal was applied. A 300 mm thick layer of pumpable, non-segregating, saturated tailings slurry at 65% solids content was then placed over the geomembrane. The assembly was completed with a mechanism to apply the desired effective stress at the top of the tailings. The test procedure is shown to closely mimic conditions of a large (up to 150 m high) facility [14], [15]. Tests were performed to evaluate the effect of: tailings and underliner properties; stress path to final stress state; effective stress; geomembrane type and thickness; geomembrane hole diameter; transmissivity between the geomembrane and tailings; and gap beneath the geomembrane hole (due to wrinkle / stone).

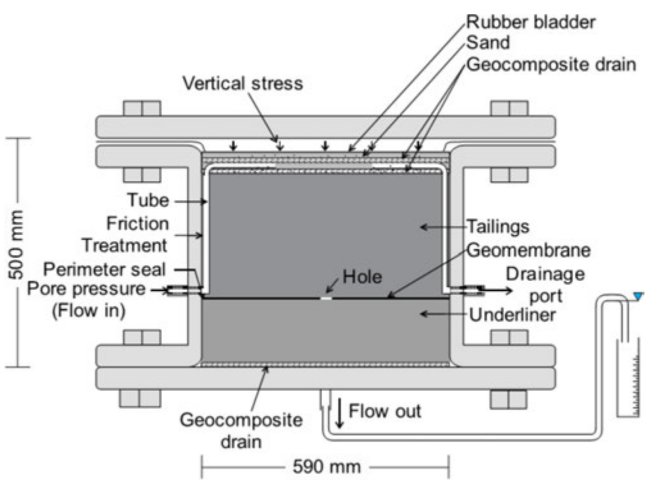

Fig. 2

Schematic of apparatus (0.5 m high and 0.59 m diameter) showing 0.14 m of compacted underliner and 0.3 m of tailings slurry.

Schéma de l'appareil (0.5 m de hauteur et 0.56 m de diamètre), montrant 0.14 m de sols compactés et 0.3 m de boues de résidus.

Table 1
Properties of materials used in the test

MATERIAL	GRAIN SIZE (MM)					% FINES (DIA. <75μM)	HYDRAULIC CONDUCTIVITY *K* (M/S)
	D_{85}	D_{50}	D_{10}	C_U	C_C		
Tailings	0.27 – 0.35	0.08 – 0.19	0.01 – 0.02	10 – 18.4	2.5 – 2.9	12 – 45	$1.6x10^{-6}$ – $2.9x10^{-8}$
Underliners	0.35 – 12	0.18 – 9.5	0.01 – 6	1.6 – 18.4	0.98 – 2.9	<1 – 27	$1x10^{-2}$ – $6.2x10^{-7}$
Geotextile	AOS = 0.15 mm					-	$5.7x10^{-3}$ (Spec. sheet)

4.2. Leakage rate

In all cases, where piping did not occur, the leakage was much lower than that predicted using those relationships for cases where the geomembranes are overlain and underlain by permeable materials. The key conclusions of the research included: 1) the overlying tailings with lower k had a larger effect on flow through the holes than the underliners examined (provided the underliner met the filter compatibility requirements). The measured flows were 4 to 5 times lower than that calculated using finite-element seepage models where a uniform k for the tailings and the underliner was assumed; 2) with a transmissive layer (geotextile) present above the geomembrane, there was a modest increase in flow through the hole. There was, however, a decrease in interface transmissivity of the geotextile due to the fines migrating into the geotextile pore spaces; 3) for the tested materials and conditions, the leakage through a 10 mm and 20 mm-diameter hole were essentially the same whereas the leakage through a 1.5 mm-diameter hole (close to being a pin hole) was three orders of magnitude lower; 4) geomembrane thickness and type had no effect on the flow; and, 5) in all cases, a non-linear decrease in flow with increase in effective stress was observed and was attributed to a larger reduction in permeability of the tailings at higher applied stresses.

4.3. Internal erosion and piping

A test using a pea gravel underliner and a 10 mm-diameter hole in the geomembrane, indicated that internal erosion and piping failure occurred. This observation has led to the Phase 2 of the research program that will be discussed in future publications and is focussed on assessing the piping processes and their implications on liner foundation design. The key observations from the current test program included: 1) placement of a filter geotextile between the geomembrane and the pea gravel underliner prevented piping and the measured flow was only slightly larger than with a silty sand underliner; 2) for a 1.5 mm-diameter hole in a geomembrane above pea gravel, there was no evidence of piping, suggesting that the size of the hole directly influences the piping potential; 3) evidence of fines migration into the pore space of geotextile or silty sand in contact with the tailings were observed, although the migrating fines potentially reduced the k locally in and around the geomembrane hole and could be reflected in the lower measured flow in the experiments.

4.4. Effect of wrinkles

Tests were carried out with various configurations of wrinkles and holes and the main conclusions of the program include: 1) a geomembrane wrinkle (without a hole) below saturated tailings experienced a larger lateral deformation than that reported for wrinkles below a gravel backfill under same applied vertical stress.The larger deformation was attributed to the hydraulic stresses applied on the wrinkle surface due to the lower shear stiffness of the overlying tailings compared to the gravel backfill where lateral stresses were lower due to arching; 2) the extent of wrinkle deformation depended on the geomembrane stiffness. For the less stiff (1 mm-thick LLDPE and HDPE) geomembranes, the deformations were larger in that both inner sides of the wrinkles were in contact at an applied vertical stress of 250 kPa - for stiffer, 2 mm-thick HDPE and LLDPE geomembrane wrinkles, the initial gap beneath the wrinkle was reduced in both height and width but remained as a wrinkle up to an applied total stress of 1000 kPa; 3) for wrinkles with a hole present prior to tailings placement, tailings migrated into the gap beneath the wrinkle and filled the gap with tailings. Measured leakage through a hole placed in the wrinkle (before or after wrinkle deformation under stress) was the same, suggesting there was no effect on leakage after tailings migrated into the wrinkle; and 4) thinner geomembranes experienced asymmetrical deformations and much larger strains.

5. PRACTICAL IMPLICATIONS AND DESIGN CONSIDERATIONS

5.1. Estimating leakage through tailings geomembrane liner systems

The knowledge on leakage through geomembrane holes in a typical landfill setting largely overestimates the expected leakage in a tailings configuration. For example, the leakage calculated by Rowe [9] for a landfill lined with a single geomembrane liner installed on a compacted clay liner and subjected to a hydraulic head of 0.3 m is over three orders of magnitude than those observed for much higher hydraulic head (higher than 60 m) in a TSF configuration. If a drainage layer is required for regulatory reasons, one must recognize that installation of a drainage layer in contact with the geomembrane will provide easier access for fluids to migrate to the geomembrane hole, thereby increasing the leakage rate. Consequently, the practice of placing drains over geomembrane liners for tailings is not considered by the authors to be good practice.

Leakage through holes in tailings / geomembrane systems is influenced by the permeability of the overlying tailings and the underliner as shown on Fig. 3 and there are significantly lower leakage rates in tailings / geomembrane liner systems than with typical landfill / liner systems. For example, the calculated leakage rates for a relatively high permeability tailings overlying a geomembrane with various QA-QC levels, overlying a foundation soil of “typical” permeability, is summarized in Table 2.

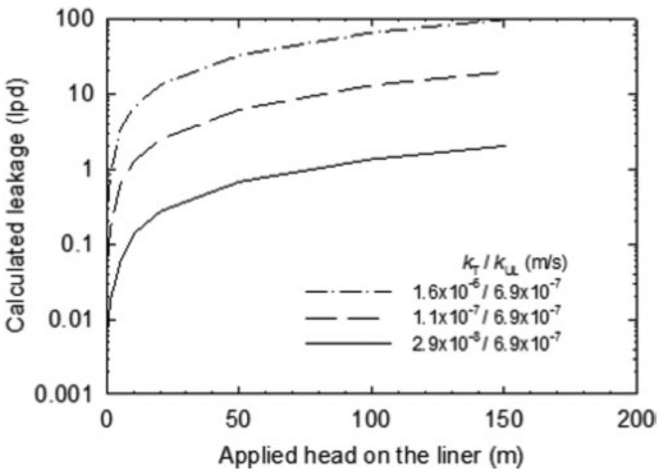

Fig. 3 [16]
Calculated leakage through a 10 mm-diameter hole in a 1 mm-thick geomembrane with different tailings permeability over a soil underliner under different head conditions.
Écoulement calculé d’une fuite au travers d’un trou de 10 mm de diamètre dans une géomembrane d’une épaisseur de 1 mm sur sol de fondation, selon la perméabilité des résidus et la pression hydrostatique.

Table 2
Leakage Flow Rates for Tailings / Geomembrane Liner System with different QA-QC Control

CALCULATION BASIS	NUMBER OF HOLES PER HECTARE	TAILINGS K (M/S)	UNDERLINER K (M/S)	FLOW		
				LPD	L/S/HA	L/S/KM^2
Measured flow in liters per day (lpd) through single hole in the test apparatus at p' = 1500 kPa	1	$1.6x10^{-6}$	$6.2x10^{-7}$	7	$8.1x10^{-5}$	$8.1x10^{-3}$
Very good QA/QC	5			35	$4.1x10^{-4}$	$4.1x10^{-2}$
Average QA/QC	15			105	$1.2x10^{-3}$	$1.1x10^{-1}$
Poor QA/QC [3]	26			182	$2.1x10^{-3}$	$2.1x10^{-1}$

Number of holes are for landfill quality QA/QC. Pin holes are not considered for the calculation.

5.2. Control of piping

Recognizing that some holes are likely in most practical cases and that seepage forces will promote piping of tailings, it is important to consider a filter-compatible foundation. In cases where a smooth foundation preparation is challenging, a geotextile cushioning layer installed below the geomembrane could also provide protection against liner damage and resist piping. Ongoing research is being carried out to further investigate the piping mechanisms.

5.3. Influence of wrinkles

It is practically impossible for a large facility to have a wrinkle-free installation. To minimize the possibility of having a network of buried wrinkles acting as conduits a less stiff geomembrane, such as an LLDPE, that easily deforms to the foundation would be preferred. With gaps beneath the geomembrane wrinkle remaining, Chappel [7] calculated leakage in a landfill liner system to be over 100 liters per day per hectare (lpdh) in a wrinkle network of 1000 m (which is possible in a large facility). However, with tailings filling the gaps below the wrinkle, the leakage assessment from the laboratory testing was shown to be orders of magnitude smaller. A large wrinkle deformation could be expected in a TSF configuration, which could lead to a higher geomembrane strain and likelihood of stress cracks. Thus, it is important to keep the length of the wrinkle network to a minimum possible. Covering the liner under low temperature conditions (e.g., early morning or late evening) has shown to make a significant difference. It may also be reasonable to be able to accommodate a larger percentage of stress cracks in a tailings / geomembrane liner system, depending on the environmental control of allowable leakage.

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