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The Effect of Local Contact Variability on Interface Transmissivity and Implications for Mine Waste Covers

Farah B. Barakat & R. Kerry Rowe
Department of Civil Engineering – Queen's University, Kingston, Ontario, Canada

ABSTRACT
Studies have shown that the interface transmissivity between a geomembrane (GMB) and geosynthetic clay liner (GCL) is scale dependent and decreases with increasing area over which the interface transmissivity is evaluated. This paper shows that this can also be expected with increasing wetted distance away from a hole in a geomembrane or hole in a wrinkle in a geomembrane. This has significance with respect to the leakage that can be expected, particularly in lower stress applications such as in covers/caps on waste disposal facilities. Measured transmissivities, obtained from a series of tests conducted at different stress levels, show that at 10 and 25 kPa, there is substantial variability in inferred transmissivity due to initial subtle differences in contact conditions from tests with a contact area of 180 cm^2. However, this testing also provides statistical data defining the distribution of the transmissivity resulting from subtle variations in contact conditions at different stress levels. This paper examines the implications of this variability with respect to the leakage through a hole in a wrinkle in a geomembrane over a geosynthetic clay liner as a function of the stress on the interface. It is shown that at overburden stresses of 10 and 25 kPa, when one considers (i) the statistical distribution of transmissivity over a range of four orders of magnitude for an area of 180 cm^2, together with (ii) continuity of flow, then one can explain the observed decrease in transmissivity at a larger scale. Based on this, the effects on potential leakage through composite liners in mine waste covers are reported.

RÉSUMÉ
Des études ont montré que la transmissivité de l'interface entre une géomembrane (GMB) et un revêtement d'argile géosynthétique (GCL) dépend de l'échelle et diminue avec l'augmentation de la zone sur laquelle la transmissivité de l'interface est évaluée. Cet article montre que cela peut également être prévu avec l'augmentation de la distance mouillée loin d'un trou dans une géomembrane ou d'un trou dans une ride dans une géomembrane. Cela a une signification en ce qui concerne les fuites qui peuvent être attendues, en particulier dans les applications à faible contrainte telles que les couvercles / bouchons des installations d'élimination des déchets. Les transmissivités mesurées, obtenues à partir d'une série de tests effectués à différents niveaux de contrainte, montrent qu'à 10 et 25 kPa, il existe une variabilité substantielle de la transmissivité présumée en raison de différences subtiles initiales dans les conditions de contact des tests avec une zone de contact de 180 cm2. Cependant, ces tests fournissent également des données statistiques définissant la distribution de la transmissivité résultant de variations subtiles des conditions de contact à différents niveaux de contrainte. Cet article examine les implications de cette variabilité en ce qui concerne la fuite à travers un trou dans une ride dans une géomembrane sur un revêtement d'argile géosynthétique en fonction de la contrainte sur l'interface. On montre que pour des contraintes de mort-terrain de 10 et 25 kPa, quand on considère (i) la distribution statistique de la transmissivité sur une gamme de quatre ordres de grandeur pour une surface de 180 cm2, ainsi que (ii) la continuité de l'écoulement, puis une peut expliquer la diminution observée de la transmissivité à plus grande échelle. Sur cette base, les effets sur les fuites potentielles à travers les revêtements composites dans les couvertures de déchets miniers sont signalés.

1 INTRODUCTION

In many hydraulic containment applications, composite liners comprised of a geomembrane, GMB, on a geosynthetic clay liner, GCL, are commonly used. The GMB and GCL layers are never in perfect direct contact with each other. This can be because of imperfections present in either component of the composite liner (e.g., local variations in the mass per unit area of bentonite and thickness of GCL, it's variations in the thickness of the cover geotextile, and variations in the intrusion of bentonite from GCL into the cover geotextile and interface itself). A parameter called the interface transmissivity, denoted by θ, is used to represent the resistance to fluid flow at the contact between the two layers. It has dimension of [L^2T^{-1}] and is usually presented in terms of (m^2/s).

Geomembranes are known to have a high coefficient of thermal expansion. Thus, when a geomembrane is laid and left exposed in direct sunlight in the field, it will frequently develop wrinkles to accommodate the extra material arising from the thermal expansion. In addition, even with good construction quality assurance, holes are bound to develop in the GMB. Wrinkles are particularly prone to damage when cover soil is placed over the geomembrane (Gilson-Beck 2019, Rowe 2020b). When a hole is present in a wrinkle, this wrinkle can act as a conduit for the easy movement of the fluid passing through the hole. This will result in flow through the GCL in the unstressed zone beneath this wrinkle. In addition, the interface transmissivity between the GMB and GCL on either side of the wrinkle can allow fluid to migrate laterally at the interface between the GMB/GCL for a distance known as the wetted distance (denoted herein by a). The magnitude of the wetted distance depends on the interface transmissivity, the hydraulic conductivity of the GCL, and the pressure head, h, on the GCL interface below the wrinkle.

The pressure head, h, in the interface between the GMB-GCL decreases with distance away from the wrinkle. Taking the top of the GCL as a datum, the head h reduced to zero (h=0) at a distance called the minimum wetted distance and denoted by a_o (Figure 1). The total area of GCL between the wrinkle and the distance a_o will be effectively saturated. If the water table is below the GCL then the interface head, h, will continue to decrease until the suction is equal to the distance, C, between the top of the GCL and the location of zero pressure head (h= -C; Figure 1) at a distance a. In this zone between the wetted distance a_o (h = 0) and the distance a ($h \sim -C$), the GCL and in particular the soil below the GCL will be unsaturated. The unsaturated flow will depend on the unsaturated hydraulic conductivity of the soil which will be low at high suctions and will approach the saturated hydraulic conductivity as the suction approaches zero. This zone is rather complicated and beyond the scope of this paper. For the purposes of this paper, consideration will be given to the leakage that occurs in the saturated zone extending to the wetted distance a_o (h=0).

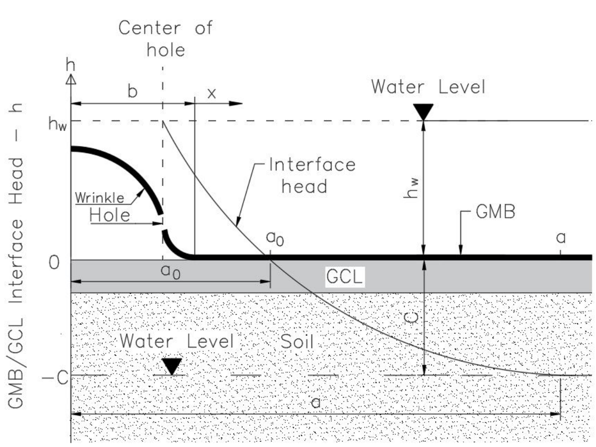

Figure 1. Schematic showing the decrease in head at the interface between the GMB and GCL with distance away from the wrinkle for the case with the water table in the soil is a distance C below the geomembrane.

The hydraulic conductivity of the GCL, k_{GCL}, is variable depending on the applied stress. Thus, there are two specific values of k_{GCL} of relevance to leakage through a holed wrinkle. Where the GMB is generally in contact with the GCL and the GCL is under pressure due to the confining stresses being applied on the composite liner, k_{GCL} is denoted by k_a. Below the wrinkle, overburden stresses arch over the wrinkle and the GCL is unconfined, k_{GCL} will generally have a higher hydraulic conductivity, denoted by k_b, than when the GCL is subjected to an applied stress (i.e., $k_b > k_a$). Thus, the leakage rate, or flow, Q (m^3/s), through a hole in the wrinkle both beneath the wrinkle and over the wetted distance a_o either side of the wrinkle is given by Equation 1 (Rowe 1998):

$$Q = 2L\left[k_{sb}b + \frac{k_{sa}}{\propto}\left(1 - e^{-\propto(a_0 - b)}\right)\right]\frac{h_d}{D} \quad [1]$$

where,

$$\propto = [\frac{k_{sa}}{D\theta}]^{0.5} \quad [2]$$

L is the length of the wrinkle, k_{sb} is the harmonic mean of the hydraulic conductivities of the unstressed portion of the GCL and foundation layer below the GCL, i.e.,

$$k_{sb} = D / (H_{GCL} / k_b + H_{AL} / k_{AL}) \quad [3]$$

$$D = H_{GCL} + H_{AL} \quad [4]$$

k_{sa} is the harmonic mean of the hydraulic conductivities of the GCL where it is under stress (in direct contact with the GMB) and the foundation layer below the GCL, b is half of the width of the wrinkle, $h_d = h_w + C$ is the difference between the total head at the top of the GCL (where there is a hole in a wrinkle) and the total head at the elevation of zero pressure head, and θ is the interface transmissivity between the GMB and GCL. The pressure head (or suction) is zero at depth C below the top of the GCL. If the GCL is resting on a drainage layer then C is the thickness of the GCL under the applied stress (i.e., $C = H_{GCL}$).

The wetted distance, a_o, can be calculated from (Rowe 1998):

$$a_o = b - [ln(C/(h_w+C)]/\alpha \quad [5]$$

where h_w is the pressure head on the top of the GCL (where there is a hole in a wrinkle), the other parameters are as previously defined. Note that α is a function of θ [Eq.2] and hence, from Eq. [5], $a_o = fn(\theta)$.

Most of the physical and hydraulic parameters in Eqs. 1-5 are well-known to geotechnical engineers with the notable exception of the interface transmissivity, θ. The object of this paper is to examine how θ varies as a function of differential head, h_d, GCL hydraulic conductivities, k_b and k_a, and the overburden stress, σ_v, for applications which typically involve low applied stress (specifically, 10 and 25 kPa in this paper) such as caps/covers over waste for a range of heads above the geomembrane between 0.05 m and 0.45 m.

2 INTERFACE TRANSMISSIVITY

Studies have shown that when holed wrinkles are present in the GMB of composite liners subjected to low stresses, the interface transmissivity varies around the small region surrounding the wrinkle; it decreases along with an increase in the scale at which the transmissivity is assessed (Rowe 2020a). Thus, the objective of this paper is to examine how the uncertainty associated with the transmissivity over a small region, as obtained in typical laboratory tests, at 10 and 25 kPa, affects the transmissivity applicable in practical situations. In addition, the paper will examine the effect of the hydraulic conductivity of the GCL that is in direct contact with the GMB, k_a, on the extent of the wetted distance and the flow that can occur beneath a holed wrinkle. This will be done by considering the statistical variability of the interface transmissivity over a small area (169 cm^2) for any specific case under consideration by calculating the harmonic mean of the range of transmissivities along the wetted distance applicable to the specific case. Lastly, this paper will identify the extent of the impact of the water head applied on the cover on the wetted distance and flow beneath the holed wrinkles for different GCL's having different hydraulic conductivities. Thus, the impacts of all the afore-mentioned parameters on the final leakage or flow that can pass through the cover in mine waste facilities and eventually contribute to ground water contamination will be evaluated.

3 METHOD

3.1 Base Cases and Parameters Considered

In this paper, two base cases will be assessed. Both cases consist of a composite liner laid on top of a 0.3 m thick foundation layer. This foundation layer was assumed to be a sandy material with a hydraulic conductivity of k_{AL} = 1x10^{-5} m/s (although anywhere in the range 1x10^{-6} < k_{AL} < 1x10^{-4} m/s will have little effect on the results presented). Furthermore, the total area considered and covered by the mine waste was taken to be a unit area of 1 ha with a length and width of 100 m. The thickness of the GCL, H_{GCL}, was taken to be 0.01m while its hydraulic conductivity under applied stress, k_a, was 6x10^{-11} m/s and under essentially zero stress (below the wrinkle), k_b, was 6x10^{-10} m/s. The applied water head on the composite liner, h_w, was 0.15 m for the base cases at 10 and 25 kPa and the pressure head was taken to be zero at the bottom of the GCL (i.e., h_a = 0.3 m). The wrinkle width after the cover soil had been placed, *2b*, was taken to be 0.1 m and, the radius of the hole in the wrinkle is 5.64 mm. It is further assumed that there was one holed wrinkle per hectare of the cover area of the mine tailings considered. For both cases, these parameters remain constant unless otherwise stated. The only difference between the two cases is the overburden stresses applied on the composite liner for each case as shown in Figure 2.

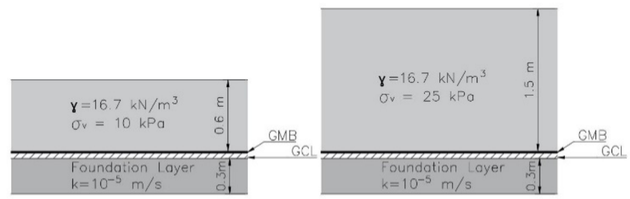

Figure 2. Schematic of the Two Base Cases

3.2 Assessing the Change in Transmissivity Away from the Wrinkle

Using Jabin's (2020) experimental data regarding the transmissivity values obtained from multiple tests under the same overburden stresses, a geometric mean and standard deviation was calculated and used to probabilistically assess all the transmissivity values for each 0.13 m x 0.13 m patch or area (169 cm^2) of the composite liner where there is direct contact at an applied overburden stress of 10 kPa. Similar calculations were conducted for an overburden stress of 25 kPa. A Monte Carlo simulation was set up that generated 5000 random transmissivities from a lognormal distribution with the mean and standard deviation obtained from Jabin's (2020) data within any assumed wetted distance. The harmonic mean of the random variables represented the transmissivity of each 0.13 m x 0.13 m patch (area) between the edge of the wrinkle and the wetted distance. Thus, the transmissivity at a distance of x = 0.26 m (Fig. 1) is the harmonic mean of the random variable corresponding to patch from the edge of the wrinkle x = 0 to x= 0.13 m and the patch x = 0.13 to x =0.26 m, and the transmissivity at a distance of x = 0.39 m is the harmonic mean of the random variable corresponding to patch from 0 to 0.13 m, the patch 0.13 to 0.26 m, and 0.26 to 0.39 m away from the wrinkle, etc for each of the 5000 realizations in the Monte Carlo simulation. Based on the 5000 evaluations of the harmonic mean at each incremental distance, x, from the wrinkle, a lognormal probability density function (with a geometric mean and standard deviation) was established for the transmissivity at any given distance from the edge of the wrinkle to each such incremental distance was obtained in multiples of 0.13 m. For the purposes of this paper, the mean value was used to represent the transmissivity at incremental distances, x, away from the wrinkle. In a subsequent paper, the probability distribution will be used to evaluate the leakage taking account of the statistical variability that will occur for each 0.13 m length of the wrinkle but, for the purpose of this paper, it is assumed that there is no difference in transmissivity as a function of position along the wrinkle.

The transmissivity values calculated were plotted against the distance x in Figure 3 and as shown, the calculated $\theta(x)$ decreased as x increased until it reached a constant value. This occurred for both 10 and 25 kPa but is more evident for the lower stress 10 kPa since the interface transmissivity values are higher. Thus, this observation demonstrates the validity of previous suggestions that the interface transmissivity decreases with increasing scale of measurement and consequently as it moves away from the wrinkle, especially for low applied overburden stresses. The important role played by stress in reducing θ with distance is particularly evident when comparing the curves for 10 and 25 kPa in Figure 3 where θ tends to 1 x 10^{-9} m^2/s at 10 kPa and 1 x 10^{-11} m^2/s at 25 kPa.

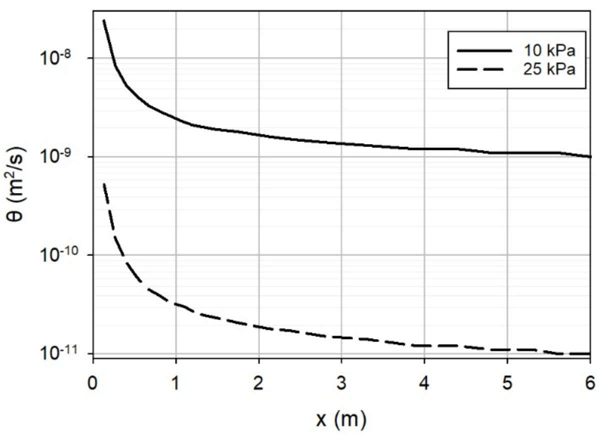

Figure 3. Mean Transmissivity versus Wetted Distance Beyond the Edge of the Wrinkle

3.3 Calculating and Allocating the Properties of the Base Cases Considered

To calculate and assign a specific wetted distance, a_o, where $a_o = fn(\theta)$ and interface transmissivity, θ, where $\theta = fn(a_o)$ for the two base cases defined earlier, an iterative process is required. The equations for calculating flow (Eq. 1) and wetted distance for $h=0$ (Eq. 5) (Rowe 1998) were used. The equations were solved iteratively using the relationship for $\theta(x)$ shown in Figure 3.

4 ANALYSIS AND RESULTS

Based on the method outlined above, the calculated flow and wetted distance for the defined base cases were 17.1 lphd (liters per hectare per day) and 1.6 m at a confining stress of 10 kPa and 10.7 lphd and 0.4 m at an applied confining load of 25 kPa respectively for one, 100 m long holed wrinkle per hectare.

4.1 Impact of Using GCL's with Different Hydraulic Conductivities on Leakage

The hydraulic conductivity of the GCL reflects the resistance to the passage of water through the GCL. Thus, the higher the values of k_a and k_b, the greater the leakage through the hole in the wrinkle, other things being equal. The impact of k_a and k_b on flow was analyzed by keeping all the parameters for both base cases constant and only changing the hydraulic conductivity of the GCL. Several different combinations of k_a and k_b were considered (Table 1). The flow and wetted distance, a_o, of each of these combinations were estimated using the approach outlined above, and Figures 4 and 5 were developed for 10 and 25 kPa respectively.

At an applied stress of 10 kPa, the flow passing through the wrinkle significantly increases as k_a is increased. The effect of k_a is less at a 25kPa applied stress (Figure 5) than at 10 kPa (Figure 4).

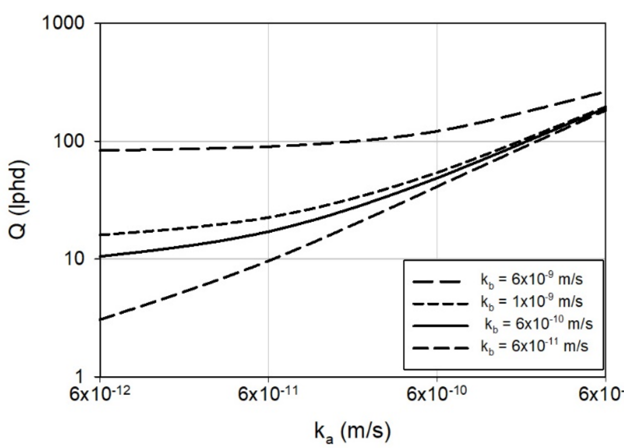

Figure 4. Q vs. k_a at Varying k_b Values (10 kPa, h_w=0.15m; L_w=100 m/ha))

Table 1. GCL Hydraulic Conductivity Combinations

	k_a (m/s)			
k_b=6x10^{-9} m/s	6x10^{-12}	6x10^{-11}	6x10^{-10}	6x10^{-9}
k_b=1x10^{-9} m/s	6x10^{-12}	6x10^{-11}	6x10^{-10}	6x10^{-9}
k_b=6x10^{-10} m/s	6x10^{-12}	6x10^{-11}	6x10^{-10}	6x10^{-9}
k_b=6x10^{-11} m/s	6x10^{-12}	6x10^{-11}	6x10^{-10}	6x10^{-9}

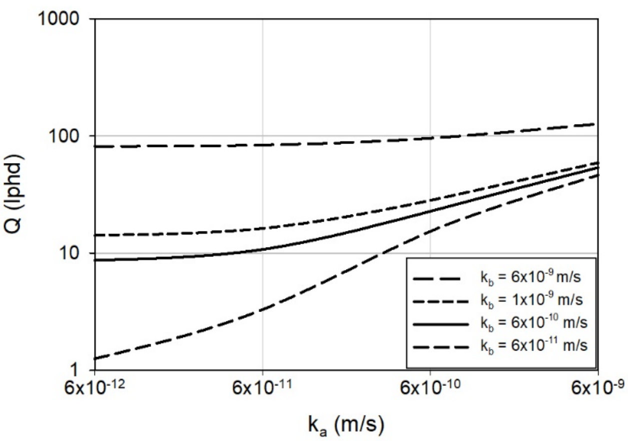

Figure 5. Q vs. k_a at Varying k_b Values (25 kPa, h_w = 0.15m, L_w=100 m/ha)

4.2 Impact of Applied Water Head on the Wetted Distance under GCL's with Different k_a

As the hydraulic conductivity k_a increased, the wetted distance a_o decreased (Figures 6 and 7). This is because it became easier for the water to flow down through the GCL than to migrate a significant distance at the interface between the GCL and GMB. However, an increase in head on the liner increased the wetted distance (Figures 6 and 7) because the greater driving force associated with the greater head forced the water further out along the interface in addition to increasing the leakage below the wetted distance. This effect was greatest at low stress (e.g., at 10 kPa; Figure 6) and was reduced at higher stresses (e.g., at 25 kPa; Figure 7).

For a confining stress of 25 kPa, the range of calculated wetted distances under different applied water heads is much lower compared to that of 10 kPa (especially at low k_a values). In addition, the calculated wetted distances for a 25 kPa stress in all the cases are significantly lower with a maximum value of 1.02 m at k_a= 6 x 10^{-12} m/s and h_w = 0.45 m compared to 5.26 m calculated for the same parameters with a 10 kPa applied stress on the liner. Although the difference in the wetted distance is not as significant for a change in h_w under a confining stress of 25 kPa compared to that at 10 kPa, the converging trend of a_o as k_a increases is still notable.

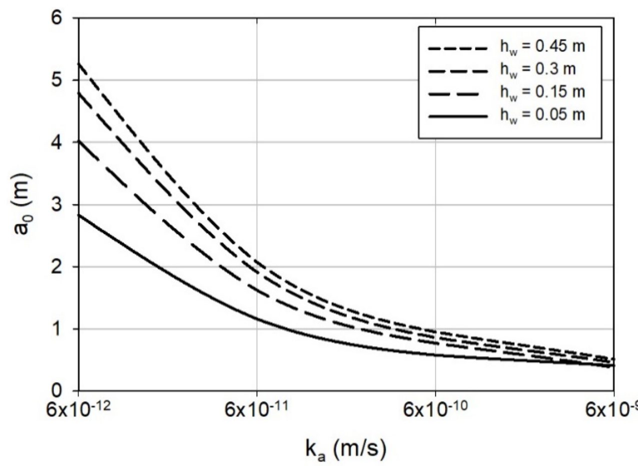

Figure 6. a_o vs. k_a for Different Heads, h_w, above the Liner – 10 kPa

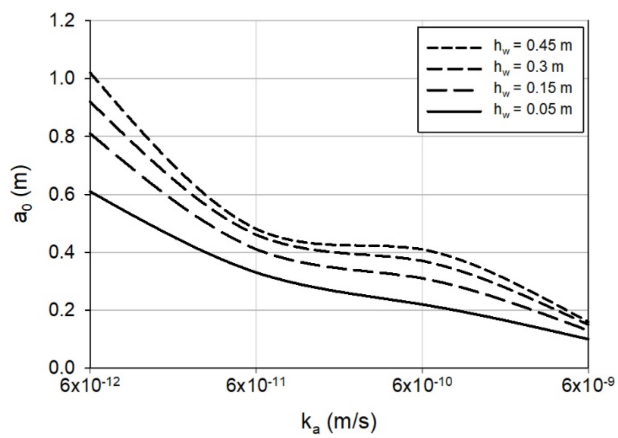

Figure 7. a_o vs. k_a for Different Heads, h_w, above the Liner – 25 kPa

4.3 Impact of Changes in Head, h_w, above the Liner on Leakage under Different GCL's

In the previous section, the impact of changing the water head, h_w, above the composite liner and k_a of the GCL on the wetted distance was examined by re-calculating the parameters of the base cases under different h_w and k_a values. Using the same calculations, the impacts of these changes on the flow passing through the holed wrinkle is analyzed in this section. Figures 8 and 9 were generated from the results of the calculations showing the change in flow at different k_a and h_w values. Both figures show that under the same head, h_w, the flow increases marginally with an increase from k_a = 6 x 10^{-12} m/s to 6 x 10^{-11} m/s. Once k_a exceeds 6 x 10^{-11} m/s, all the curves show a notable increase in slope representing relatively large changes in flow with an increase in k_a. Furthermore, a comparison of Figures 8 and 9, shows that the effect of an increasing k_a is much more significant at 10 kPa than at 25 kPa applied stress because of the substantial difference in transmissivity between 10 and 25 kPa. This highlights the importance of considering the stress dependence and role of interface transmissivity when attempting to predict the leakage through mining covers involving a composite liner.

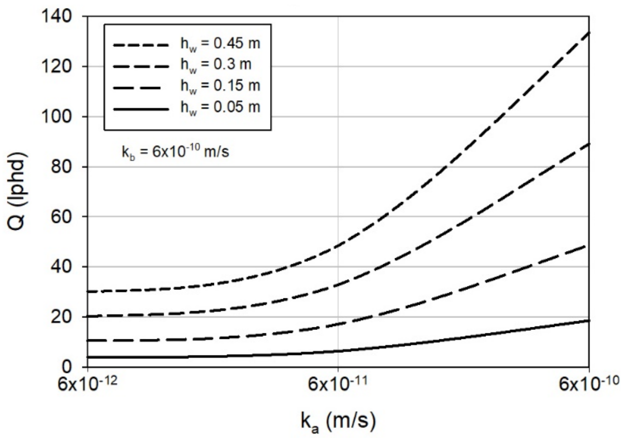

Figure 8. Q vs. k_a for Different Heads, h_w, above the Liner (10 kPa; kb=6x10^{-10} m/s; L_w=100 m/ha)

The results shown in Figures 8 and 9 are analyzed for the base k_b value (hydraulic conductivity beneath the wrinkle with no direct contact with the GMB) of the GCL, 6 x 10^{-10} m/s. Thus, to see the impact of changing k_b on flow, the same calculations were remade for a k_b value of 6 x 10^{-9} m/s and, the results obtained are shown in Figures 10 and 11. Unlike the previous case with a lower k_b value, the figures show that under the same h_w value, the flow remains nearly constant with a very small increase for a greater range of k_a, 6 x 10^{-12} m/s < k_a < 6 x 10^{-10} m/s. Once k_a exceeds 6 x 10^{-10} m/s, all the curves show a notable increase in slope representing large changes in flow with an increase in k_a beyond that point.

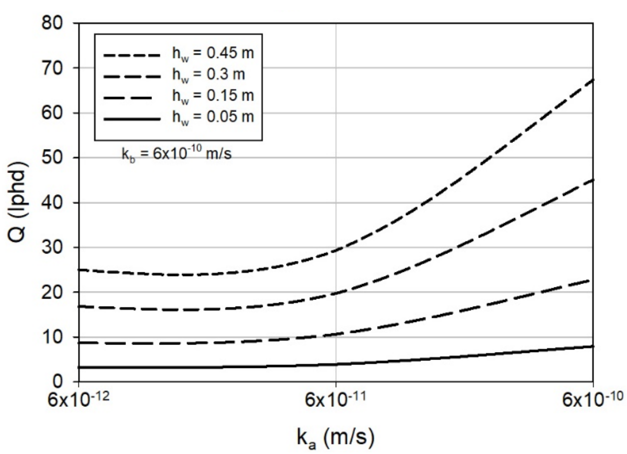

Figure 9. Q vs. k_a Different Heads, h_w, above the Liner (25 kPa; k_b=6x10^{-10} m/s; L_w=100 m/ha)

The flows calculated for the k_b value of 6 x 10^{-9} m/s are much greater than those obtained previously for the k_b value of 6 x 10^{-10} m/s and that is due to the larger capacity of flow that is capable to move through the GCL beneath the width of the wrinkle due to this increase in k_b. The slope increase of the curves beyond 6 x 10^{-10} m/s is maximum for that representing the highest h_w value, 0.45 m, and minimum for the curve representing the lowest h_w value, 0.05 m, which represents the same trend to the curves developed in Figures 8 and 9. Comparing Figures 10 and 11 also shows that the changes in slope with increasing k_a is much more significant for a 10 kPa than 25 kPa stress on the composite liner which allows for a similar presumption that the degree of flow change as k_a increases beyond 6 x 10^{-10} m/s is much more impactful for covers with low applied overburden stresses because of the much higher interface transmissivity at low stress.

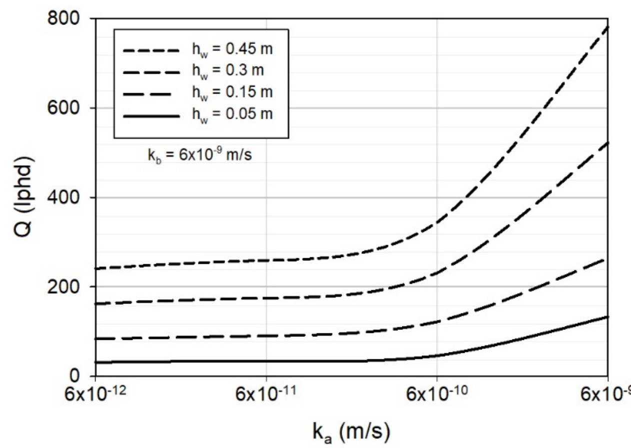

Figure 10: Q vs. k_a Different Heads, h_w, above the Liner (10 kPa; k_b=6x10^{-9} m/s; L_w=100 m/ha)

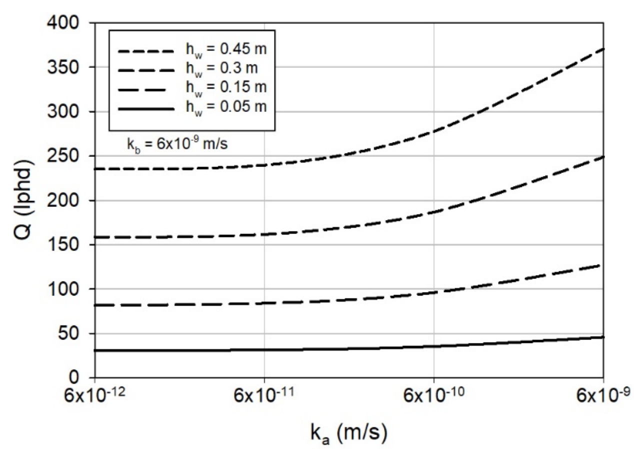

Figure 11: Q vs. k_a Different Heads, h_w, above the Liner (25 kPa; k_b= 6x10^{-9} m/s; L_w=100 m/ha)

4.4 Significance of considering the change in transmissivity with distance as compared to simply using the value obtained from laboratory test without considering statistical variability

Without adopting the approach illustrated in this paper, one could calculate the leakage and wetted distance from Eqs. 1 and 5 using the mean value of $2.4x10^{-8}$ m^2/s at 10kPa and $5.2x10^{-10}$ m^2/s at 25 kPa obtained as a geometric mean from the tests performed by Jabin (2020). For a range of combinations of k_a and k_b giving values of leakage Q and wetted distance a_o shown in Table 2 at 10 kPa and Table 3 at 25 kPa, the calculated leakage using the laboratory average θ gave a wetted distance more than 4-fold and 3-fold greater, respectively, than the more rigorous consideration of the effects of statistical variability in transmissivity with distance as presented in this paper. The lab average value of θ gave leakage Q more than 3-fold higher for k_b = $6x10^{-11}$ m/s and about 2-fold higher for k_b = $6x10^{-10}$ m/s at 10 kPa and, more than 50% higher for k_b = $6x10^{-11}$ m/s and 10% higher for k_b = $6x10^{-10}$ m/s at 25 kPa. This highlights the importance of using laboratory data to provide insight but not relying on just a few tests to obtain values to be used directly without considering statistical variability, particularly at low stresses.

Table 2. GCL Hydraulic Conductivity Combinations at 10 kPa, L_w=100 m, h_w =0.15, H_{GCL}=0.01, H_{AL}=0.3m

k_{GCL}		Lab mean		This method	
k_b (m/s)	k_a (m/s)	a_o (m)	Q (lphd)	a_o (m)	Q (lphd)
$6x10^{-11}$	$6x10^{-12}$	17.5	10.7	4.0	3.1
$6x10^{-11}$	$6x10^{-11}$	5.6	32.0	1.7	10.2
$6x10^{-10}$	$6x10^{-12}$	17.5	18.1	4.0	10.5
$6x10^{-10}$	$6x10^{-11}$	5.6	39.4	1.6	17.1

Table 3. GCL Hydraulic Conductivity Combinations at 25 kPa, L_w=100 m, h_w =0.15, H_{GCL}=0.01, H_{AL}=0.3m

k_{GCL}		Lab mean		This method	
k_b (m/s)	k_a (m/s)	a_o (m)	Q (lphd)	a_o (m)	Q (lphd)
$6x10^{-11}$	$6x10^{-12}$	2.6	2.3	0.8	1.3
$6x10^{-11}$	$6x10^{-11}$	0.9	5.4	0.5	3.3
$6x10^{-10}$	$6x10^{-12}$	2.6	9.7	0.8	8.7
$6x10^{-10}$	$6x10^{-11}$	0.9	12.9	0.4	10.6

5 SUMMARY OF RESULTS

Based on the lognormal distribution of the interface transmissivity (and the corresponding geometric mean and standard deviation) reported by Jabin (2020) at 10 and 25 kPa confining stress, five thousand randomly generated transmissivities were generated. These transmissivities were used in the Monte Carlo calculation of the geometric mean effective (harmonic mean) transmissivity between the edge of a holed wrinkle and a distance, x, beyond the wrinkle. It was shown that the mean effective transmissivity decreased with distance, x, away from the wrinkle. The transmissivities calculated for the different x values were then used to calculate the wetted distance and corresponding leakage (flow rate) using Rowe's (1998) equations for a series of cases in the two stresses of interest.

The analyzed cases showed that an increase in k_a (the hydraulic conductivity of the GCL while the GMB and GCL are in direct contact) results in a somewhat exponential increase in flow. This increase is most significant for the case where the GCL had low k_b. For $6x10^{-12}$ m/s < k_a < $6x10^{-10}$ m/s, the higher the k_b values used, the higher the flow calculated to be passing through the holed wrinkle and into the subgrade. As k_a increased beyond $6x10^{-10}$ m/s, a change in k_b resulted in a less significant impact on flow and the curves converged to eventually result in a similar flow for both confining stresses considered. It should be noted that the flows calculated for composite liners under a confining stress of 25 kPa were generally lower than those experiencing a 10 kPa confining stress.

As k_a increased, the wetted distance developed and calculated decreased. For $6x10^{-12}$ m/s < k_a < $6x10^{-10}$ m/s, an increase in the head on the liner results in an increase in the calculated wetted distance. As k_a increases beyond $6x10^{-10}$ m/s, a change in the applied water head, h_w, had a less significant impact on the wetted distance and a_o seems to converge to a single value.

Lastly, the impact of a change in k_a and h_w on flow was analyzed. Although the wetted distance and thus, the area through which there is leakage decreased with increasing k_a, the flow showed an increasing trend. For k_b = $6x10^{-10}$ m/s, the flow under both confining stresses remained constant with small changes as the k_a increased from $6x10^{-12}$ m/s to $6x10^{-11}$m/s. Once k_a exceeded $6x10^{-11}$m/s, the increase in flow with increasing k_a was much more significant especially for lower confining stresses (10 kPa). As h_w increased, the calculated flow further increased; the impact of a change in h_w on the calculated flow magnified as k_a increased. For k_b = $6x10^{-9}$ m/s, similar observations were seen. The only difference was that the flow experienced minor increases over a larger range of k_a, $6x10^{-12}$ m/s < k_a < $6x10^{-10}$ m/s. Large changes in flow were observed as k_a exceeded $6x10^{-10}$ m/s.

6 CONCLUSION

Based on recent data, the effects of the statistical variability in the transmissivity over small areas of the interface between a geomembrane and GCL was used to evaluate the variation in transmissivity with distance away from the edge of a wrinkle in a geomembrane with a hole. Using data from this analysis, calculations were performed to show the variability in both the wetted distance and the leakage that might be expected through covers in mining cover/capping applications for a range of parameters with particular emphasis on situations where there was sufficient cover soil to apply a stress of 10 and 25 kPa to the composite liner. Subject to the assumptions made in the range of parameters examined, the following general conclusions were reached:

- The interface transmissivity decreases with distance *x* from the edge of a wrinkle until it asymptotes to a constant value at a given overburden stress.
- There is a substantial difference in interface transmissivity at stress levels of 10 and 25 kPa. Thus, there can be substantially more leakage for a thin cover in applying overburden pressure of 10 kPa to the interface than for a thicker cover applying 25 kPa.
- Careful consideration must be given to the effect of the applied stress and cation exchange on the effective hydraulic conductivity of a GCL both directly beneath a wrinkle (where it is unstressed) and where the stress corresponds the overburden pressure.
- Leakage is sensitive to the hydraulic conductivity below the geomembrane and since this hydraulic conductivity is stress dependent, one can anticipate higher leakage under an overburden stress of 10 kPa than 25 kPa. The difference in hydraulic conductivity is both because of the effect of the applied stress and because with a thinner amount of cover soil, the GCL is more likely to be affected by freeze-thaw conditions.
- Results of this analysis highlight the role played by the applied overburden stress on the potential for leakage; and provide support for the need to pay careful attention to selecting appropriate thickness of cover material of a composite liner.

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