RATE OF LIQUID FLOW THROUGH COMPOSITE LINERS DUE TO DEFECTS IN THE GEOMEMBRANE: RECENT ADVANCES

Quantificação do fluxo através de orifícios na geomembrana: desenvolvimentos recentes

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Abstract: This paper presents the recent advances on the existing methods for evaluating the rate of advective flow through composite liners. The advective flow is due to the existence of defects in the geomembrane and depends on the features of interface between the geomembrane and the underlying liner, which can be expressed either by the interface transmissivity, or by contact conditions. Direct methods (laboratory tests), and indirect methods (analytical equations, empirical and semi-empirical equations and numerical analysis) are addressed. The main goal of this work is to provide design engineers with a review of the tools currently available to calculate the advective flow through composite liners.

1 INTRODUCTION

Modern landfills are generally designed to protect the environment against contaminants by using a composite liner. In this type of liner, the geomembrane (GM) provides the primary resistance to advective contaminant flow (also termed leakage, and herein simply referred to as flow) as well as to diffusion of some contaminants. The clay component of the composite liner, compacted clay liner (CCL) or geosynthetic clay liner (GCL), serves to reduce the flow through inevitable holes or defects in the geomembrane. It also provides some attenuation of contaminants that can diffuse through intact geomembranes or transfer through holes in the geomembranes.

Unfortunately, despite all precautions regarding manufacturing, transportation, handling, storage and installation, defects in the GM seem to be unavoidable. Defects in the GM represent preferential advective flow paths for leachate migration.

The impact of the defects in the GM can be minimised by proper design of the landfill liner. It is thus of primary importance to predict the flow rate through composite liners due to the existence of defects in the GM.

Tools currently available for predicting flow rates through composite liners for situations where there exists an interface between geomembrane and soil liner include the direct methods, namely laboratory tests, and indirect methods, such as analytical solutions, empirical equations and numerical modeling.

The main goal of this paper is to present recent advances on the existing methods for assessing the flow rate through composite liners due to defects in the GM, with particular emphasis on the indirect methods as they are the ones typically used in designing the confining systems.

2 GEOMEMBRANE DEFECTS

2.1 Cause of defects

Defects in the GM result generally from construction activities, such as improper seaming, punctures by stones in the support or cover material, dropped objects, tears, excessive stresses caused by equipment traffic, failures from subsidence or shear failures of the supporting soil after installation, imperfect connections between GM and appurtenances, etc.

For covered geomembranes (case of landfills), it seems that most defects appear during the placement of the primary leachate collection system (PLCS). Results presented by Nosko & Touze-Foltz (2000) from electrical damage detection systems installed at more than 300 sites, from 16 countries, covering over 3 250 000 m^2, showed that the majority of the damages (71%) were caused by stones during PLCS installation, 16 % by heavy equipment, 6 % by inadequate seams, 6% by the workers, and 1% by cuts (Figure 1). Similar conclusions were drawn by Colucci & Lavagnolo (1995) from the analysis of 30 leak location surveys conducted in Italy, covering more than 300 000 m^2. According to these authors, the number and the quality of the defects were related to the quality of the subgrade material, the quality of the cover material, the accuracy in their installation and the quality of the liner installation.

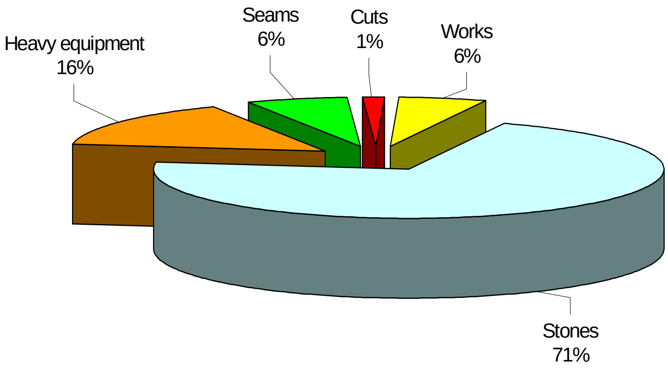

Figure 1 – Cause of defects in geomembrane liners after installation of the cover layer (data from Nosko & Touze-Foltz 2000)

As for the effects of the subgrade materials, it must be pointed out that modern landfills often incorporate a GCL. Although there is no data available on this topic, when the geomembrane is placed over a GCL, it can be expected that a negligible number of defects be caused by the underneath materials.

2.2 Defects density

Another issue related with this topic is the defects density per liner area, i.e. number of defects per hectare (Colucci & Lavagnolo 1995). The variation of defect density as a function of the area of the facility surveyed is plotted in Figure 2. It can be observed that the density of defects tends to decrease as the surveyed area increases. However, it must be noted that there are many uncertainties regarding the varying conditions found in different sites (different types of geomembranes, different facilities, covered and uncovered geomembranes, etc). According to Colucci & Lavagnolo (1995), the reasons for the higher defects densities found in small installations can be summarised as follows: (1) smaller facilities have proportionally more complex features (corners, sumps, penetration); (2) small facilities tend to have higher percentage of hand seaming (extrusions); (3) large facilities have a stricter construction quality program; (4) large installations generally receive less traffic. Similar observations have been drawn by other authors, such as, for example, Rollin et al. (1999, 2004).

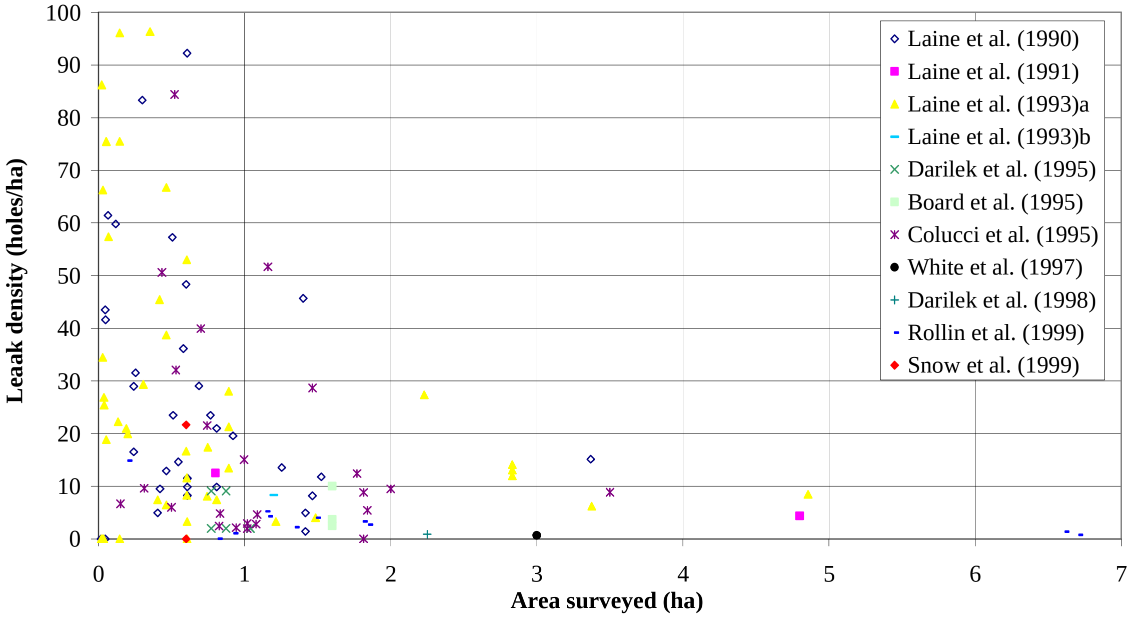

Figure 2 – Variation of defect density as a function of the area surveyed (from Touze-Foltz 2001)

Table 1 shows defect densities presented by different authors for covered GMs. It can be seen that they range from 0.7 to 15.3 defects/ha. Results of the same order of magnitude were reported by Forget et al. (2005). These authors summarising 10 years of leak detection surveys on GM, found a defect density of 0.5 defects/ha for covered GM installed under a strict construction quality assurance (CQA) program compared to a defect density of 16 defects/ha in absence of a CQA program.

It should be noted that relatively higher defect densities can be found on small containment facilities with complex features to deal with, and where the GM is placed directly on the subgrade-soil. For example, Laine et al. (1989) reported a mean density of 26 defects/ha from surveys conducted on small containment facility (less than 2 ha).

Table 1 includes the mean values obtained by Touze-Foltz (2001) from a synthesis of studies involving electrical leak location systems. Surveys assessed included: Laine & Mosley (1993), Board & Laine (1995), Colucci & Lavagnolo (1995), White & Barker (1997), Darilek & Miller (1998), Snow et al. (1999). This author reports a mean defect density of 2.8 per hectare after installation of the geomembrane and 11.9 per hectare after placement of the granular drainage layer. This result confirms that the majority of the defects occur during placement of the granular layer above the geomembrane.

Table 1 – Reported defect density (modified from Touze-Foltz 2001)

Reference	Area surveyed (ha)	Status of geomembrane	Defects on geomembrane sheet (%)	Defects on geomembrane seams (%)	Mean defect density (defect/ha)
Laine & Mosley (1993)	1	Covered	20	80	8.3
Board & Laine (1995)	2	Covered	31	69	5.5
Colucci & Lavagnolo (1995)	25	Covered	85	45	15.3
White & Barker (1997)	1	Covered	100	0	0.7
Darilek & Miller (1998)	1	Covered	100	0	0.9
Snow et al. (1999)	2	Covered	100	0	10.9
Nosko & Touze-Foltz (2000)	325	Covered	93.7	6.3	12.9
Touze-Foltz (2001)	108.8	Covered	81.5	18.5	11.9

Another interesting aspect pointed out refers to defects occurred in the long term. Needham et al. (2004) reported data from electrical leak detection surveys using permanent systems. Data were obtained from 88 cells and 18 leachate lagoon at 55 landfill sites in Eastern Europe, Belgium and the United Kingdom, covering approximately 1 022 000 m^2. Results were reviewed from a survey company over a 7-year period, from 1996 to 2003. According to these authors, the number of defects was 1 460 (14.3 defects/ha), with 74 % located during the initial leak survey at the end of liner construction and 26 % of the defects being detected in subsequent surveys. As regards the defects detected on later surveys reported by Needham et al. (2004), most of them (78 %) were caused by stone puncturing in consequence of traffic movement over empty cells. Needham et al. (2004) do not include detailed information about the cause of the defects, however reported data draw attention to the possibility of damages occurring during operation of the landfill.

Results of a permanent in situ system (grid system) at a landfill in UK since installation in 1995 are also reported by Needham et al. (2004). A liner area of 5.5 ha is covered by this system. The monitoring at that landfill site has so far given a defect density of 16 holes/ha. Of these holes 27 % were detected after completion of the liner, before waste disposal started in the cell or after landfilling began. In addition, there is no evidence of gradual development of holes from 1995 to 2003. Based on these results, the authors concluded that once a liner is covered by several meters of waste, the agents for future development of holes in liner are limited and they are unlikely to develop for at least the first decade of the service of the geomembrane liner.

Summarising, reported data suggest that the number and density of defects depend on the size of the facility. Small defect densities were found in larger facilities. This can be attributed mainly to the proportionally less complex features (corners, sumps, pipes penetration, etc.) of the larger facilities, as well as to the small percentage of hand seaming. The implementation of strict CQA programmes also seems to have a great impact on the number of defects. Large defect densities are usually reported for sites constructed without CQA programmes. A frequency ranging from 0.5 to 15.3 defects/ha can be expected in landfills.

This defects density seems to be in agreement with the values previously recommended by Giroud & Bonaparte (1989) for design calculations. According these authors a frequency of 12 defects/ha should be considered. The US EPA Help program assumes a default defect density of 2.5 holes per hectare for “excellent” installation quality and from 2.5 to 10 defects/ha for “good” installation quality (Schroeder et al. 1994).

2.3 Type and size of defects

Table 2 presents data reported by different authors about type and size of defects. It can be seen that Colucci & Lavagnolo (1995) found that approximately 50 % of all detected defects were smaller than 1 cm^2 with larger defects being the holes and tears. Rollin et al. (1999) found that the smallest defects (< 0.02 cm^2) represented 43% of the detected defects and were mainly associated with seam failures, whereas the largest defects (> 0.1 cm^2), representing 22.4 % of the total, were more related to holes and cuts. Nosko & Touze-Foltz (2000) observed that 50 % of the defects fall into a range of 0.5 to 2.0 cm^2, 24.9 % of the defects varied from 2.0 to 10 cm^2, 14.3 % exceeded 10 cm^2, and 10.8 % were less than 0.5 cm^2. An interesting aspect of their study is that the defects related with heavy equipment were typically larger than 10 cm^2, whereas the majority of the defects related to seams (83 %) were less than 2 cm^2. In addition, Peggs (2001) found that the most common defect was a puncture between 0.2 and 1 cm in diameter.

It can be observed that the sizes of the defects reported by Rollin et al. (1999) are smaller than those from other authors included in Table 2. This is due to the fact that their results are related to uncovered geomembrane liners and defects in geomembranes can be much larger after placement of the overlying drainage materials, as pointed out by Colucci & Lavagnolo (1995), Nosko & Touze-Foltz (2000), and Peggs (2001).

From Table 2 the following general comments can be made: (1) the majority of the holes are smaller than 10 cm^2, which would correspond to a circular hole of 3.6 cm in diameter; (2) seams are not bonded over lengths ranging from 1 mm to more than 1 m; (3) cuts can reach more than 1 m; and (4) most tears are smaller than 1 m long.

For design calculations, circular defect sizes typically used are 1 cm^2 (diameter of 11.28 mm) and 3.14 mm^2 (diameter of 2 mm). These values were recommended by Giroud & Bonaparte (1989) for flow rate calculations in case of GMs installed under a strict construction quality assurance programme. As can be inferred from the above discussion, these defect sizes do not take into account damage to the GM caused by the placement of the granular layer over the GM. Therefore, for design purposes, larger diameters than the one suggested by Giroud & Bonaparte (1989) should also be considered.

Table 2 – Defect size as a function of defect type (Barroso 2005)

Reference	Size	Holes	Tears/burns/ equipment	Cuts/ scraps/ gouges	Seams	Sites	Area surveyed (ha)
Colucci & Lavagnolo (1995)	0-0.2 cm^2	44	31	12	11	25	27.6
	0.2-1 cm^2	37	49	21	4		
	1-5 cm^2	60	49	2	8		
	5-10 cm^2	22	11	0	4		
	10-100 cm^2	10	22	0	1		
	100-1000 cm^2	15	4	0	0		
	1000-8400 cm^2	0	5	0	0		
Rollin et al. (1999)	<0.02 cm^2	3	-	0	18	11	24.1
	0.02-0.1 cm^2	6	-	4	7		
	> 0.1 cm^2	3	-	6	2		
Nosko & Touze-Foltz (2000)	< 0.5 cm^2	332		5	115	300	325
	0.5-2 cm^2	1720	236	36	105		
	2-10 cm^2	843	153	18	30		
	> 10 cm^2	90	496	-	15		
Peggs (2001)	< 0.1 cm	10	0	4	2	1	63.4
	0.2-1 cm	28	9	7	5		
	1-5 cm	7	2	21	3		
	5-10 cm	0	1	5	3		
	10-50 cm	1	0	2	1		
	50-100 cm	0	0	0	3		
	> 100 cm	0	0	2	2		
	unknown	4	1	5	3		

3 EXISTING TOOLS FOR EVALUATING THE FLOW THROUGH COMPOSITE LINERS

There are several methods for evaluating the flow rate through composite liners due to defects in the GM. These methods can be grouped in two different categories: direct methods and indirect methods.

Direct methods include laboratory tests, such as the ones carried out by Fukuoka (1986), Jayawickrama et al. (1988), Estornell & Daniel (1992), Harpur et al. (1993), Touze-Foltz (2001, 2002), Touze-Foltz et al. (2002a, 2006, 2007), Koerner & Koerner (2002), Cartaud et al. (2005), Chai et al. (2005) and Barroso et al. (2005, 2006). The reader is referred to these sources for further information on laboratory testing.

Indirect methods include analytical solutions, empirical and semi-empirical equations and numerical analysis. Before addressing these methods it is important to underline that the flow through a defect in the GM depends on the contact between the GM and the underlying liner as indicated by Brown et al. (1987). According to these authors, once fluid has migrated through the defect, it then spreads laterally through the interfacial zone between the geomembrane and the underlying liner (this interface flow covers an area called wetted area) and, finally, the liquid migrates into and through the soil liner (Figure 3).

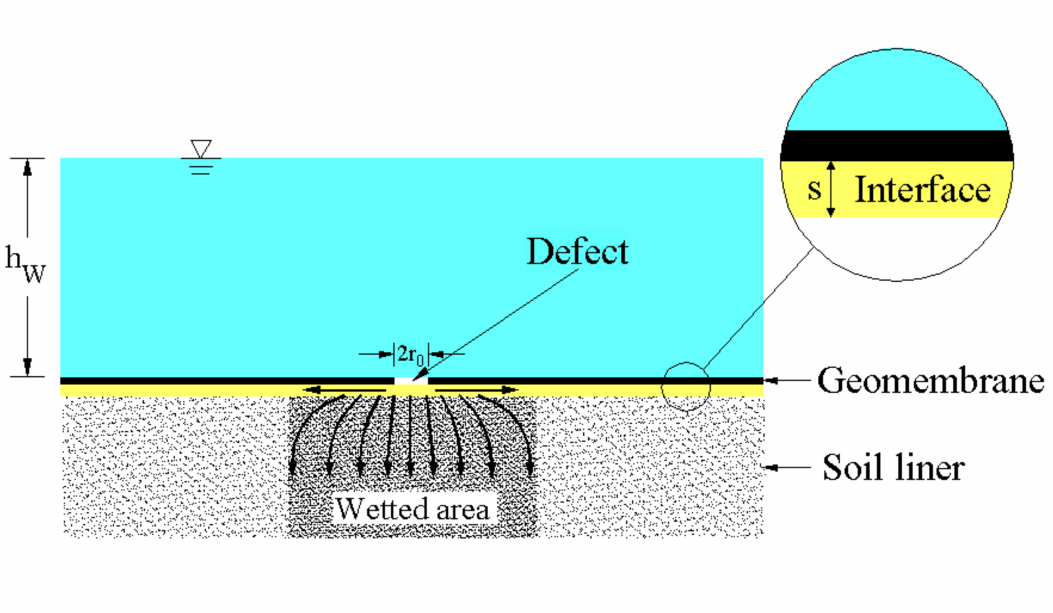

Figure 3 – Liquid flow through a composite liner due to a defect in the GM (Barroso 2005)

There are three main sources of imperfect contact between a GM and a soil liner according to Rowe (1998): (i) protrusions related to particle size distribution in the liner material, which create a gap in which the fluid may flow; (ii) undulations/ruts which result in the surface not appearing smooth, and (iii) wrinkles in the GM.

Focusing on the quality of the GM installation, three GM-CCL contacts are typically considered: excellent, good and poor contact conditions. The definitions of good and poor contact conditions were initially defined by Giroud (1997), based on the original concept by Giroud et al. (1989). The excellent contact condition was added to the previous ones by Touze-Foltz & Giroud (2003). Definitions of these contact conditions are presented below:

- Poor contact conditions correspond to a GM that has been installed with a certain number of wrinkles, and/or has been placed on a low-permeability soil that has not been adequately compacted and does not appear smooth;
- Good contact conditions correspond to a GM that has been installed with as few wrinkles as possible, on top of a low permeability soil layer that has been properly compacted and has a smooth surface. Furthermore, it is assumed that there is sufficient compressive stress to maintain the GM in contact with the low-hydraulic conductivity soil layer; and
- Excellent contact conditions correspond to a GM that has been installed with no wrinkles, on top of, and in close contact with, a low-hydraulic conductivity soil layer (or GCL) that has been adequately compacted and has a very smooth surface. Furthermore, it is assumed that there is sufficient compressive stress to maintain the GM in contact with the layer underneath.

Qualitative definitions of contact conditions are subjective. This may lead to different interpretations of a given field case. To overcome this limitation, Rowe (1998) proposed quantitative definitions linking the soil liner hydraulic conductivity to the interface transmissivity for poor and good contact conditions. These quantitative definitions were extended by Touze-Foltz & Giroud (2003) for excellent contact conditions. Later on, Barroso (2005) proposed a new contact condition, which they termed as GM–GCL contact condition, based on experimental data. Quantitative definitions of contact conditions are given below:

$$log\,\theta = -1.7476 + 0.7155\,log\,k_L \qquad \text{for excellent contact conditions} \qquad (1)$$

$$log\,\theta = -1.3564 + 0.7155\,log\,k_L \qquad \text{for good contact conditions} \qquad (2)$$

$$log\,\theta = -0.5618 + 0.7155\,log\,k_L \qquad \text{for poor contact conditions} \qquad (3)$$

$$log\,\theta = -2.2322 + 0.7155\,log\,k_{GCL} \qquad \text{for GCL–GM contact conditions} \qquad (4)$$

where θ is the hydraulic transmissivity of the interface, k_L is hydraulic conductivity of the soil in contact with the GM, and k_{GCL} is the hydraulic conductivity the GCL component of the composite liner. Equations 1 to 4 can only be used with the following units: θ (m^2/s) and k (m/s).

3.1 Analytical solutions

A number of analytical solutions have been developed to quantify the flow rate through defects in flat or wrinkled geomembranes based on Darcy's law (e.g. Brown et al. 1987; Jayawickrama et al. 1988; Rowe 1998; Touze-Foltz et al. 1999, Touze-Foltz et al. 2001), where the interface between the geomembrane and the underlying layer is of uniform thickness and, consequently, where the hydraulic transmissivity is uniform.

The most commonly used equations were proposed by Rowe (1998) and Touze-Foltz et al. (1999). The first author developed analytical equations to quantify liquid flow for the case of a circular hole in a flat geomembrane and in a wrinkled geomembrane. Touze-Foltz et al. (1999) extended the solution for a damaged wrinkle for various boundary conditions and to the problem of liquid flow for two, or more, parallel interacting damaged wrinkles. Equations by Touze-Foltz et al. (1999) were again extended by Touze-Foltz et al. (2001) to take into account the non uniform hydraulic transmissivity at the interface geomembrane/CCL or geomembrane/GCL.

The basic problem configuration follows from Rowe (1998) and Touze-Foltz et al. (1999) and is depicted in Figure 4. It includes a geomembrane resting on a low–permeability soil layer of thickness H_L and hydraulic conductivity k_L. This layer can be either a CCL or a GCL. From now on, it will be simply designated as "soil liner". The z-axis origin corresponds to the top of the soil liner with upward being positive. The soil liner rests on a more permeable foundation or attenuation layer of thickness H_f and hydraulic conductivity k_f, which, in turn, rests on a highly permeable layer that can be either an aquifer or a secondary collection layer. Accordingly, it can be assumed that the flow through the composite liner is not influenced by the hydraulic conductivity of subgrade layers. It is assumed that the features of the interface (contact conditions) can be characterised by a uniform hydraulic transmissivity, θ. The interface transmissivity that governs interface flow can be established either based on experimental data, or on empirical equations (equations 1 to 4).

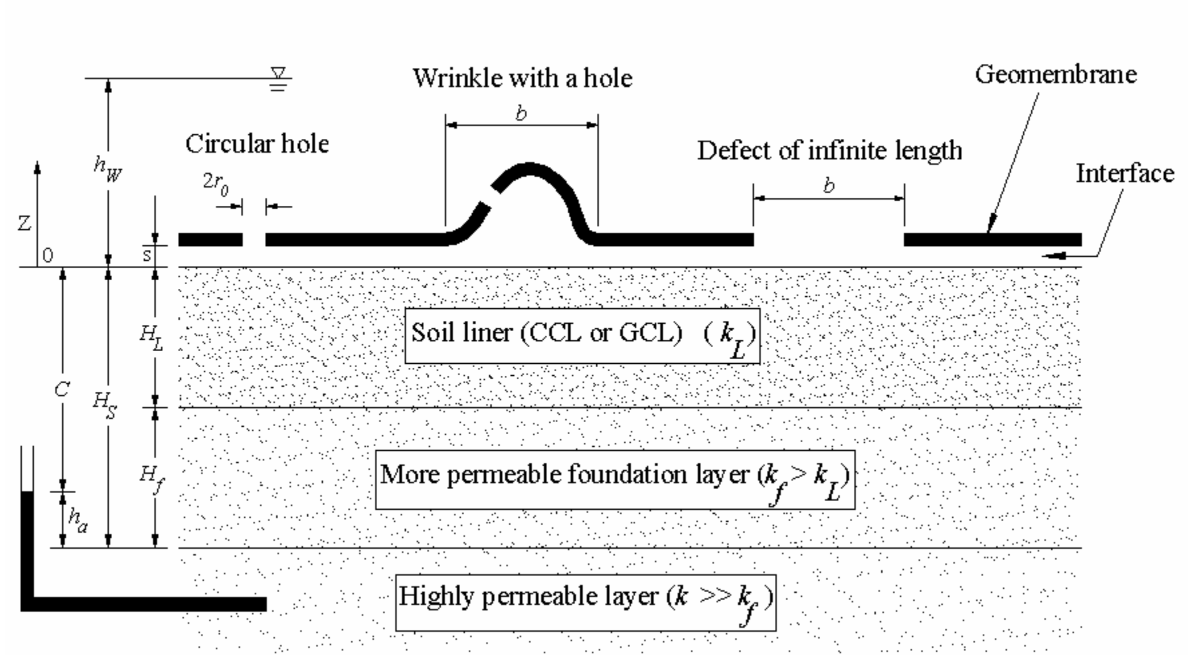

Figure 4 – Schematic drawing showing a composite liner with a geomembrane exhibiting different types of defects: circular hole of radius r_0, a damaged wrinkle of width b, and a defect of infinite length and width b (modified from Touze-Foltz et al. 1999)

Furthermore, it is assumed that: (i) liquid flow is under steady-state conditions; (ii) the soil liner and the foundation layer are saturated; (iii) liquid flow through the liner and the foundation layer is vertical (Rowe 1998, Touze-Foltz et al. 1999). According to the continuity of liquid flow, the equivalent hydraulic conductivity, k_s, corresponding to the liner and the foundation layer is given by (Rowe 1998, Touze-Foltz et al. 1999):

$$\frac{H_L + H_f}{k_s} = \frac{H_L}{k_L} + \frac{H_f}{k_f} \tag{5}$$

When a hydraulic head, h_w, is applied on the top of the composite liner, the mean hydraulic gradient, i_s, through the liner and foundation is given by (Rowe 1998, Touze-Foltz et al. 1999):

$$i_s = \frac{H_L + H_f + h_w - h_a}{H_L + H_f} = 1 + \frac{h_w - h_a}{H_L + H_f} \tag{6}$$

where h_a is the hydraulic head in the highly permeable layer that is not fully saturated, and often assumed to be equal to zero.

3.1.1 Case of a circular defect in the GM

The analytical solution obtained by Touze-Foltz et al. (1999) for a flow in the interface equal to zero at a distance R_c from the defect centre in GM corresponding to the radius of the wetted area for saturated conditions in the composite liner can be written as:

$$Q = \pi r_0^2 k_s i_s - 2\pi r_0 \theta\beta\left[A_p I_1(\beta r_0) - B_p K_1(\beta r_0)\right] \tag{7}$$

Where

$$\beta = \sqrt{\frac{k_s}{\left(H_L + H_f\right)\theta}} \tag{8}$$

$$A_p = -\frac{(h_w + C)K_0(\beta R_c) - (h_s + C)K_0(\beta r_0)}{K_0(\beta r_0)I_0(\beta R_c) - K_0(\beta R_c)I_0(\beta r_0)} \tag{9}$$

$$B_p = \frac{(h_w + C)I_0(\beta R_c) - (h_s + C)I_0(\beta r_0)}{K_0(\beta r_0)I_0(\beta R_c) - K_0(\beta R_c)I_0(\beta r_0)} \tag{10}$$

$$C = H_L + H_f \tag{11}$$

In these equations K_0 and I_0 are modified Bessel functions of zero order. Parameter R_c is obtained by solving Equation 12 (zero hydraulic head at radius R_c):

$$AI_0(\beta R_c) + BK_0(\beta R_c) - H_s = 0 \tag{12}$$

3.1.2 Case of a damaged wrinkle of width *b* and a defect of infinite length and width *b*

In the case of a damaged wrinkle, flow is controlled by the “footprint” of the wrinkle, defined as the zone where the wrinkled GM is not in contact with the underlying liner (width *b* in Figure 4). From a calculations point of view, there is no fundamental difference between a damaged wrinkle of width *b* and a defect of infinite length and width *b* since it is assumed that the holes in a wrinkle do not control the flow and no assumption is made regarding the height or the shape of the wrinkle. Thus, the two types of defects are defined by a single parameter: their width *b* (Figure 4). The analysis is two-dimensional, that is why these two types defects are generally referred to as two-dimensional defects, and the rate of liquid flow is expressed in terms of rate of liquid flow per unit length.

In steady-state conditions, for saturated conditions in the composite liner, the flow rate per unit length, Q_L, can be obtained by Equation 13, given by Touze-Foltz et al. (1999):

$$Q_L = k_s \frac{h_w + H_s}{H_s} \left\{ b + 2\sqrt{\frac{\theta H_s}{k_s}} \tanh\left[\cosh^{-1}\left(\frac{h_w + H_s}{H_s} \right) \right] \right\} \tag{13}$$

Equation 13 was later on simplified by Giroud & Touze-Foltz (2005) as follows:

$$Q_L = b\ k_s \left(1 + \frac{h_w}{H_s} \right) + 2\sqrt{k_s\ \theta\ h_w \left(2 + \frac{h_w}{H_s} \right)} \tag{14}$$

As highlighted by those authors, the first term of the right side of Equation 14 quantifies the rate of flow into the soil liner (CCL or GCL) located directly under the defect. The second term quantifies the rate of interface flow.

Analytical solutions such as the ones previously have the advantage of being rigorous. For circular defects, the drawback of these tools is their complexity.

3.2 Empirical equations

Numerous empirical equations for predicting the flow rate through composite liners comprising a GM and a soil liner (CCL) due to defects in geomembranes have been developed and successively updated. Giroud & Bonaparte (1989) and Giroud et al. (1989) developed the first sets of equations. These equations provide an approximate solution assuming that the hydraulic gradient is close to unity. This assumption may be reasonable for low leachate mounds (design mounds ranging from 0.03 to 0.3 m) and clay liners with thickness of 0.6 to 0.9 m, but are not strictly valid for the levels of leachate mounding that may occur during post-operation, in cases of excessive clogging of a leachate collection system, or a modest leachate mound over a GCL (Rowe 1998). Aware of these limitations, Giroud et al. (1992) extended the approximate solution to consider higher hydraulic heads. They also proposed equations for defects of infinite length. A limitation in these equations was that they required charts to obtain the value of one of the terms of the equation.

Giroud (1997) updated previous empirical equations, providing an entirely analytical means of calculating the flow rate through defects in geomembranes. In addition, he summarised the developed equations in regard of the shapes of the defects, the liquid head above the geomembrane liner, and the contact conditions. Later on, Giroud et al. (1998) developed a new set of equations for calculating: (a) the rate of flow through composite liners due to geomembrane defects; (b) the rate of flow through defects in a geomembrane placed on a semi-permeable medium; and (c) the rate of flow through defects in a geomembrane overlain by a permeable medium and underlain by a highly permeable medium.

Foose et al. (2001) and Touze-Foltz (2001) compared the flow rate through composite liners comprising a geomembrane and a CCL calculated using either empirical equations or analytical equations. For small circular defects, the results obtained using empirical equations developed by Giroud (1997) showed good agreement with the results obtained using analytical equations developed by Rowe (1998) and Touze-Foltz et al. (1999). Conversely, for defects of infinite length, the results obtained using empirical equations by Giroud et al. (1992) were inconsistent with the results obtained using the analytical equations. Analysis conducted by Foose et al. (2001) attributed this inconsistency to the fact that the empirical equations for small circular defects and defects of infinite length correspond to different values of interface transmissivity even though the same contact conditions are considered. In other words, the interface transmissivity was a function of the type of defect, which should not happen. Based on these findings, these authors proposed new empirical equations for defects of infinite length (Foose et al. 2001) and damaged wrinkles (Touze-Foltz et al. 2002b).

Equations by Touze-Foltz et al. (2002b) were later on updated by Touze-Foltz & Giroud (2003), which also updated the empirical equations for defects of infinite length developed by Giroud et al. (1992) and proposed a new equation for excellent contact conditions (small circular defects). An important advance was reached with the new empirical equations developed by Touze-Foltz & Giroud (2003), based on the assumption that the transmissivity is independent from the type of defect. This significant improvement was in part due to the fact that they could define the contact conditions in quantitative terms (equations 1 to 3).

In order to consider the large circular defects in the GM (diameters in the 100 to 600 mm range) and the three type of contact conditions (excellent, good and poor), Touze-Foltz & Giroud (2005) developed new equations. It should be noted that empirical equations proposed by Touze-Folz & Giroud (2003, 2005) supersede previous equations presented by the same authors.

Chai et al. (2005) proposed a modification of equations by Giroud (1997), for circular defects, and by Touze-Foltz & Giroud (2003), for infinite length defects, in order to consider the effect of the effective overburden pressure applied by the waste over the lining system. Modification proposed consists to multiply the flow rate by a dimensionless correction factor that is equal to one when the overburden pressure is equal to zero.

At this point, there are empirical equations for calculating the advective flow through three types of defects in the GM: circular (small and large), defects of infinite length (tears, cuts or defective seams) and damaged wrinkles, that consider three types of contact conditions (excellent, good and poor). There is also an empirical equation for defects of infinite length that can be used for GM-GCL contact conditions (equation by Foose et al. 2001).

In fact, there are no defects of infinite length, all defects have a certain length. From a practical point of view, this artificial designation just means that the defects are so long with respect to their width that the flow at the ends of the defect can be disregarded. Unfortunately, this assumption is not always possible. In some cases, the flow effect of the ends cannot be ignored as clearly pointed out by Giroud et al. (1992), Chai et al. (2005) and Giroud & Touze-Foltz (2005). Aware of this limitation, the latest authors developed a new set of equations where the effect of the two ends is taking into account by assuming that the plan view of the defect is a rectangle with a half circle at each end (Figure 5). Equations developed by Giroud & Touze-Foltz (2005) correspond in fact to a combination of the analytical equation for long defects (Equation 14) with empirical equations for the rate of liquid flow through circular defects in the GM. These equations are herein termed as semi-empirical equations. Again, these equations were developed for the three GM-CCL contact conditions, namely excellent, good and poor.

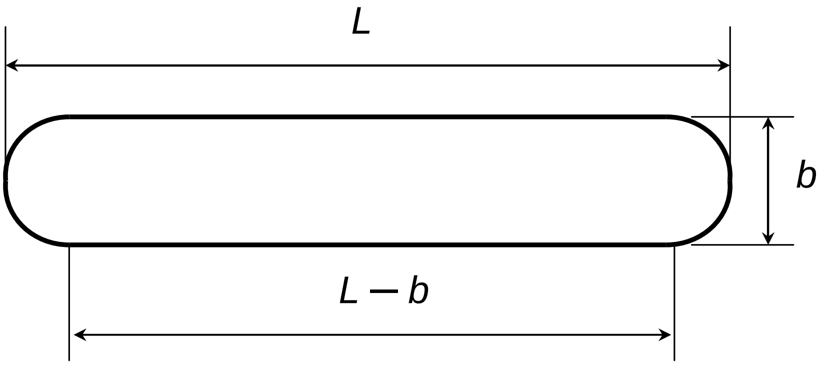

Figure 5 – Plan view of a defect of finite length (Giroud & Touze Foltz 2005)

As emphasized by Rowe (2005), when a GM is placed over a GCL, there is a greater potential for obtaining better contact with a low-permeability layer than when placed over a CCL. This is because the GCL can be placed flat on a well-compacted, smooth soil liner. As the factor controlling the flow rate for GM over the GCL is the contact conditions between the GM and the GCL, a new set of equations were proposed by Touze-Foltz & Barroso (2006) for composite liners involving GCLs. Equations by these authors included empirical equations for small and large circular defects (i.e. one for defect diameters ranging from 2 to 20 mm and other for defect diameters ranging from 100 to 600 mm), as well as semi-empirical equations to predict flow rates through defects of finite length (i.e. narrow defects, such as tears, cuts or defective seams, and wide defects, such as damaged wrinkles).

Table 3 summarises the latest empirical equations for assessing the flow rate through composite liners caused by circular defects in the geomembrane. Equations given in this table supersede previous equations presented by the same authors (if it is the case). Empirical equations for defects of infinite length and damaged wrinkles (two-dimensional defects) are not presented here because their utilization is no longer recommended, since the analytical solutions (as simplified by Gioud & Touze-Foltz 2005) is more rigorous and its validity is not limited to a range of parameters.

It should be noted that the empirical equations included in Table 3 can only be used for the following values of the parameters (Touze-Foltz & Giroud 2003, Touze-Foltz & Barroso 2006):

- Hydraulic heads ranging from 0.03 to 3 m;
- Hydraulic conductivities of the soil component of the composite liner ranging from 1×10^{-10} to 1×10^{-8} m s^{-1} (for excellent, good and poor contact conditions);
- Thicknesses of the soil layer component of the composite liner ranging from 0.3 to 5 m (for excellent, good and poor contact conditions);
- Hydraulic conductivities of the GCL component of the composite liner ranging

from 1×10^{-12} to 1×10^{-10} m s^{-1} (for GM-GCL contact conditions);

- Thickness values of the GCL component of the composite liner ranging from 6 mm to 14 mm (for GM-GCL contact conditions).

Table 3 – Existing empirical equations for assessing the flow rate through composite liners due to circular defects in the GM

Circular defects	**Contact conditions**	**Empirical equations**	**Reference**
2 mm< holes diameter < 20 mm	Excellent	$Q = 0.096\ h_w^{0.9}\ a^{0.1}\ k_s^{0.74}\left[1 + 0.1\left(\frac{h_w}{H_s}\right)^{0.95}\right]$	Touze-Foltz & Giroud (2003)
	Good	$Q = 0.21\ h_w^{0.9}\ a^{0.1}\ k_s^{0.74}\left[1 + 0.1\left(\frac{h_w}{H_s}\right)^{0.95}\right]$	Giroud (1997)
	Poor	$Q = 1.15\ h_w^{0.9}\ a^{0.1}\ k_s^{0.74}\left[1 + 0.1\left(\frac{h_w}{H_s}\right)^{0.95}\right]$	
	GM–GCL	$Q = 2.4\times10^{-3}\ h_w^{0.9}\ a^{0.1}\ k_s^{0.74}\left[1 + 0.1\left(\frac{h_w}{H_s}\right)^{0.95}\right]$	Touze-Foltz & Barroso (2006)
100 mm< holes diameter < 600 mm	Excellent	$Q = 0.33\ h_w^{0.84}\ a^{0.18}\ k_s^{0.77}\left[1 - 0.1\left(\frac{h_w}{H_s}\right)^{0.027}\right]$	Touze-Foltz & Giroud (2005)
	Good	$Q = 0.64\ h_w^{0.84}\ a^{0.18}\ k_s^{0.77}\left[1 - 0.1\left(\frac{h_w}{H_s}\right)^{0.027}\right]$	
	Poor	$Q = 2.60\ h_w^{0.84}\ a^{0.18}\ k_s^{0.77}\left[1 - 0.1\left(\frac{h_w}{H_s}\right)^{0.027}\right]$	
	GM–GCL	$Q = 0.116\ h_w^{0.54}\ a^{0.4}\ k_s^{0.82}\left[1 - 0.22\left(\frac{h_w}{H_s}\right)^{-0.35}\right]$	Touze-Foltz & Barroso (2006)

Note: the following symbols are used in this table: Q = flow rate; h_w = hydraulic head on top of geomembrane; a = circular defect area; k_s = soil layer hydraulic conductivity (in case of composite liners involving GCLs, it represents the equivalent hydraulic conductivity of the soil liner plus the GCL); H_s = soil + GCL layer thickness; and θ = transmissivity of the interface. These equations must be used with the following units: Q (m^3 s^{-1}), h_w (m), a (m^2), k_s (m s^{-1}), H_s (m), and θ (m^2 s).

As for narrow defects of finite length where the flow at the ends of the defect cannot be disregarded, Table 4 presents the semi-empirical equations currently available. As mentioned, semi-empirical equations couple an empirical equation for circular defects with the Equation 14. As can be inferred from Figure 5, the diameter of the circular defect, corresponding to the half-circles at the ends of the defect, is equal to the width of the defect (*b*).

Table 4 – Existing semi-empirical equations for assessing the flow rate through composite liners due to defects of finite length in the GM

Width of the defect/ diameter of the circular defect	Contact conditions	Empirical equations	Reference
$2 < b < 20$ mm	Excellent	$Q_{\mathrm{T}} = (L-b)\left[b\,k_{\mathrm{s}}\left(1+\frac{h_{\mathrm{w}}}{H_{\mathrm{s}}}\right)+2\sqrt{k_{\mathrm{s}}\theta h_{\mathrm{w}}\left(2+\frac{h_{\mathrm{w}}}{H_{\mathrm{s}}}\right)}\right]+0.094\ b^{0.2}h_{\mathrm{w}}^{0.9}k_{\mathrm{s}}^{0.74}\left[1+0.1\left(\frac{h_{\mathrm{w}}}{H_{\mathrm{s}}}\right)^{0.95}\right]$	Giroud & Touze-Foltz (2005)
	Good	$Q_{\mathrm{T}} = (L-b)\left[b\,k_{\mathrm{s}}\left(1+\frac{h_{\mathrm{w}}}{H_{\mathrm{s}}}\right)+2\sqrt{k_{\mathrm{s}}\theta h_{\mathrm{w}}\left(2+\frac{h_{\mathrm{w}}}{H_{\mathrm{s}}}\right)}\right]+0.205\ b^{0.2}h_{\mathrm{w}}^{0.9}k_{\mathrm{s}}^{0.74}\left[1+0.1\left(\frac{h_{\mathrm{w}}}{H_{\mathrm{s}}}\right)^{0.95}\right]$	
	Poor	$Q_{\mathrm{T}} = (L-b)\left[b\,k_{\mathrm{s}}\left(1+\frac{h_{\mathrm{w}}}{H_{\mathrm{s}}}\right)+2\sqrt{k_{\mathrm{s}}\theta h_{\mathrm{w}}\left(2+\frac{h_{\mathrm{w}}}{H_{\mathrm{s}}}\right)}\right]+1.12\ b^{0.2}h_{\mathrm{w}}^{0.9}k_{\mathrm{s}}^{0.74}\left[1+0.1\left(\frac{h_{\mathrm{w}}}{H_{\mathrm{s}}}\right)^{0.95}\right]$	
	GM-GCL	$Q_{\mathrm{T}} = (L-b)\left[b\,k_{\mathrm{s}}\left(1+\frac{h_{\mathrm{w}}}{H_{\mathrm{s}}}\right)+2\sqrt{k_{\mathrm{s}}\theta h_{\mathrm{w}}\left(2+\frac{h_{\mathrm{w}}}{H_{\mathrm{s}}}\right)}\right]+2.3\times10^{-3}\ b^{0.2}h_{\mathrm{w}}^{0.9}k_{\mathrm{s}}^{0.74}\left[1+0.1\left(\frac{h_{\mathrm{w}}}{H_{\mathrm{s}}}\right)^{0.95}\right]$	Touze-Foltz & Barroso (2006)
$100 < b < 600$ mm	Excellent	$Q_T = (L-b)\left[b\,k_s\left(1+\frac{h_w}{H_s}\right)+2\sqrt{k_s\theta h_w\left(\frac{h_w}{H_s}\right)}\right]+0.32\ b^{0.36}k_s^{0.77}\ h_w^{0.84}\left[1-0.1\left(\frac{h_w}{H_s}\right)^{0.027}\right]$	Giroud & Touze-Foltz (2005)
	Good	$Q_T = (L-b)\left[b\,k_s\left(1+\frac{h_w}{H_s}\right)+2\sqrt{k_s\theta h_w\left(\frac{h_w}{H_s}\right)}\right]+0.61\ b^{0.36}k_s^{0.77}\ h_w^{0.84}\left[1-0.1\left(\frac{h_w}{H_s}\right)^{0.027}\right]$	
	Poor	$Q_T = (L-b)\left[b\,k_s\left(1+\frac{h_w}{H_s}\right)+2\sqrt{k_s\theta h_w\left(\frac{h_w}{H_s}\right)}\right]+2.49\ b^{0.36}k_s^{0.77}\ h_w^{0.84}\left[1-0.1\left(\frac{h_w}{H_s}\right)^{0.027}\right]$	
	GM-GCL	$Q_T = (L-b)\left[b\,k_s\left(1+\frac{h_w}{H_s}\right)\right]+2\sqrt{k_s\theta\,h_w\left(2+\frac{h_w}{H_s}\right)}+0.111\ b^{0.8}k_s^{\ 0.82}h_w^{\ 0.54}\left[1-0.22\left(\frac{h_w}{H_s}\right)^{-0.35}\right]$	Touze-Foltz & Barroso (2006)

Note: the following symbols are used in this table: Q_L = flow rate per unit length; h_w = hydraulic head on top of geomembrane; b = diameter of the circular defect corresponding to the half-circles at the ends of the defect/ width of the defect; k_s = soil layer hydraulic conductivity (in case of composite liners involving GCLs, it represents the equivalent hydraulic conductivity of the soil liner plus the GCL); H_s = soil + GCL layer thickness; L = defect length; and θ = transmissivity of the interface. These equations must be used with the following units: Q_L ($m^2\ s^{-1}$), h_w (m), b (m), k_s ($m\ s^{-1}$), H_s (m), L (m) and θ (m^2 s).

3.3 Numerical methods

One limitation of the analytical solutions presented in Section 3.1 of this paper is that they assume total saturation of the soil liner. This implies a restriction of the validity of those equations on a limited area where saturation can be guaranteed, which is the so-called wetted area. Furthermore, as soil liners and GCLs are not initially saturated when installed, the question arises of the possibility to take account of this partial saturation in the quantification of flow. The only existing solution at the moment to study this point is numerical modelling.

Cartaud et al. (2005a) proved through numerical modelling using a finite element model that the initial hydration of the CCL has a limited impact on the flow through composite liners. Saidi et al. (2006) undertook a similar study with the same numerical code, METIS, for composite liners incorporating GCLs where significant differences between flow rates obtained thanks to analytical solutions and numerical modelling were observed. Those were attributed to the significant discrepancy between wetted area corresponding to the saturated zones calculated thanks to analytical solutions and empirical equations thus showing the importance of taking partial saturation of GCLs into account. They also studied the impact of the shape of the end of longitudinal defects on flow rates. Results obtained tended to show that while considering a circular or a square end of defect does not change much to the result, the way the longitudinal defect is decomposed will have, thus suggesting that a more precise result would be obtained through 3D numerical modelling while quantifying advective flow.

The impact of non-uniformity of interfaces opening on advective flow could also be investigated though numerical modelling. Cartaud et al. (2005b) investigated the influence of the position of a circular hole in the geomembrane of the composite liner. They could show the importance of the respective positions of the hole and of non-uniformities of the interface opening on advective flow rates, that cannot be accounted for through empirical equations or analytical solutions.

Numerical modelling can also be a useful tool while quantifying the possible hydraulic interaction between defects. If analytical solutions exist for this purpose when one is dealing with longitudinal defects, no analytical solutions allows to investigate the influence of the distance between adjacent defects on the advective flow. A recent investigation of this point was performed by Saidi et al. (2007) for GM-GCL composite liners that puts in light a very limited hydraulic interaction between adjacent square holes in the geomembrane.

4 CONCLUSIONS

This paper presented the recent advances on the existing methods for evaluating the rate of advective flow through composite liners. The advective flow is due to the existence of defects in the geomembrane and depends on the features of interface between the geomembrane and the underlying liner, which can be expressed either by the interface transmissivity, or by contact conditions. The goal of the paper was to provide design engineers with a review of the tools currently available to calculate the advective flow through composite liners.

Two different analytical solutions were presented and discussed, one for circular defects located in a flat area of the geomembrane (e.g. punctures) and the other for two-dimensional defects, either defects of any shape located on wrinkles in the geomembrane resulting in damaged wrinkles or defects of infinite length (i.e. defect that are so long with respect to their width that the flow at the ends of the defects can be disregarded). The main advantage of these equations is that they are rigorous and their main disadvantage is the complexity, especially for the case of circular holes located in an area where the geomembrane has no wrinkles.

Recent advances on empirical equations for predicting the flow rates through composite liners comprising a geomembrane and a soil liner and a geomembrane and a GCL liner were presented. Equations presented take into account four contact conditions: excellent, good, poor and GM-GCL contact condition. The main advantage of these equations is their simplicity. They are, however, valid only within a certain range of parameters.

Semi-empirical equations recently purposed for the cases that the flow at the ends of the defect cannot be disregarded (defects of finite length) were also presented. These equations also take into account the excellent, good, poor and GM-GCL contact conditions.

Finally, the paper briefly presented the results of numerical investigations undertaken through finite elements methods providing insight on the behaviour of composite liner when one is to deal with partial saturation, non-uniformity of the interface or interaction between square defects in the geomembrane that analytical solutions and empirical equations cannot predict due to their limitations.

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