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Empirical equations for calculating the rate of liquid flow through GMB-GCL composite liners subjected to cation exchange and wet-dry cycles

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ABSTRACT: The aim of this paper is to present empirical equations developed to calculate advective flow rates through composite liners for hydraulic and environmental applications. The situation studied is that of geomembranes (GMB) involving circular holes combined with aged geosynthetic clay liners (GCLs). Indeed, the alteration by the environment consisting in cation exchange and extreme climatic conditions (i.e. wet-dry cycling) is investigated in this paper. The development of these empirical equations is based on a GMB-GCL contact condition obtained from laboratory experiments, in the case of composite liners involving altered GCLs, in which, the hydraulic conductivity is larger than 10^{-10} m/s. Empirical equations were developed for circular holes with diameters in two different ranges of 2 to 20 mm and 100 to 600 mm. Results show that empirical equations developed in this study are different from previous equations using virgin GCL-GM contact condition for the different kinds of defects studied in the range of parameters studied. To analyse these differences, a comparative study was undertaken in order to review the accuracy between new empirical equations and conventional analytical solutions. Results show that the new equations are much closer to analytical solutions than conventional equations which show an improvement of the estimation of the flow rate by ta-king into account a realistic set of conditions.

1 INTRODUCTION

Composite liners used at the base of modern landfills often contain a high-density polyethylene (HDPE) geomembrane (GMB) over a geosynthetic clay liner (GCL). This GMB-GCL association is intended to minimize the leakage and transport of contaminants from the landfill to the surrounding environment (i.e., surface and groundwater). Despite special attention regarding manufacturing, transportation, handling, storage and installation, defects in the GMB seem to be unavoidable, as shown by Needham (2004) and Peggs (2015). They represent preferential advective flow paths for leachate migration which could reach and pollute the surrounding soil and groundwater. It thus seems important to correctly predict flow rates through composite liners due to the appearance of defects in the GMB in order to evaluate the potential impact of the leachate on the environment, especially on soil liners and groundwater.

Experimental (Barroso 2005, Mendes et al. 2010, Rowe & Abdellaty 2013, Touze-Foltz et al. 2002), analytical (Rowe 1998, Touze-Foltz et al. 1999) and numerical (Cartaud et al. 2005, Foose et al. 2001, Rowe & Abdellaty 2012) approaches existing in the literature have been undertaken in order to evaluate flow rate through composite liners due to defects in the GMB. However, experiments take a long time and require expensive equipment. Furthermore, the use of analytical and numerical calculations requires some effort to solve for leakage rates through the composite liner and use to consider asymmetrical properties which may not be representative of real conditions. For this reason, design engineers evaluate the flow rate by means of empirical equations.

Empirical equations for predicting the flow rate through defects in GMBs underlain by GCLs have been developed based on contact conditions and have been successively updated (Barroso 2005, Foose et al. 2001, Touze-Foltz & Barroso 2006, Touze-Foltz & Giroud 2003).

These existing empirical equations are valid for the case of virgin GCLs, or GCLs solely after cation exchange, for which the hydraulic conductivity ranges between 10^{-12} and 10^{-10} m/s.

However, the GCL can also be subjected to physical dehydration due to moisture or temperature gradients across the entire barrier that is generated by climatic conditions, especially in landfill covers or in dams (Bannour et al. 2015b, Benson 2013). Wet-dry cycles, especially in arid regions, can damage GCLs, for example by causing desiccation with cracks leading to preferential flow paths after the GCL hydrates (Lin & Benson 2000). In fact, after some cycles, desiccation cracks do not close up when the GCL rehydrates as the GCL has lost its swelling abilities (Touze-Foltz et al. 2010). This leads to large increases in hydraulic conductivity of GCLs, by as much as 4 to 5 orders of magnitude when compared to the initial value of hydraulic conductivity of virgin GCLs. This fact has been observed not only for GCLs used alone, but also for GCLs used in composite liners under the combined effect of cation exchange and wet-dry cycles.

Scalia & Benson (2010) and Bannour et al. (2015b) recently performed experiments aiming at quantifying advective flow rates in composite liners, in which a GMB is damaged, including aged GCLs due to cation exchange and wet dry cycles and generally for GCLs, in which, hydraulic conductivity was greater than 10^{-10} m/s. This has led to the development of new GMB-GCL contact conditions characterising the interface transmissivity as a function of the hydraulic conductivity of GCLs altered by their environment (Bannour et al. 2015b).

As a result, this paper aims to develop new empirical equations for calculating the GMB-GCL flow rate taking into account the alteration of GCLs by their environment. The methodology followed in this work is that proposed by Touze-Foltz & Giroud (2003).

2 BACKGROUND

2.1 *Existing empirical equations for calculating flow rate through GMB-GCL composite liners*

Giroud & Bonaparte (1989) developed the first sets of equations for predicting the flow rate through a hole in a GMB covering a low permeability clay with some approximate assumptions. In this study, the focus is on the development of empirical equations in the case when the GMB is overlying a GCL. Barroso (2005), Foose et al. (2001), Touze-Foltz & Barroso (2006) and Touze-Foltz & Giroud (2005) improved the approximate solution to consider higher ranges of parameters (hydraulic heads, shape and dimensions of defects, etc.) and contact conditions for the case when a GMB is overlying a GCL which corresponds to the case of this study. Detailed steps of the evolution of the development of empirical equations in the literature have already been detailed by Barroso (2005) and will not be repeated here.

The form of the mathematical expression for the empirical equation for circular defects is presented in Equation 1 (Giroud 1997):

$$Q = C_c\, h_w^{\chi}\, a^{\xi}\, k_s^{\kappa} \left[1 + \lambda \left(\frac{h_w}{H_s} \right)^{\mu} \right] \tag{1}$$

Where Q is the rate of flow through a composite liner, C_c is the contact condition factor, h_w is the hydraulic head on top of the GMB, a is the circular defect area, k_s is the equivalent hydraulic conductivity of the soil liner (GCL + Compacted clay liner "CCL"), λ is a factor, H_s is the equivalent thickness of the soil liner (GCL + CCL) and χ, ξ, κ and μ are exponents. Equation 1 can only be used with the SI units as follows: Q ($\mathrm{m^3s^{-1}}$), h_w (m), a ($\mathrm{m^2}$), k_s ($\mathrm{m\ s^{-1}}$), and H_s (m). The dimension of C_c is variable and χ, ξ, κ, λ and μ are dimensionless. In this equation, the term in brackets is the average hydraulic gradient (i_s,) in the soil liner (GCL + CCL).

Table 1 summarises the different empirical equations established for the different circular defects and contact conditions representative along the years of the case of GM-GCL composite liners.

Abuel Naga & Bouazza (2014) also developed empirical equations for predicting flow rate through GMB-GCL composite liners. However, their solution requires solving 11 complex equations which can be very challenging to perform. Consequently, the study will not be considered in the present paper.

It should be noted that existing empirical equations included in Table 1 for circular holes in the GMB can only be used for the following values of the parameters (Giroud & Touze-Foltz 2005, Touze-Foltz & Giroud 2003):

- small circular defects having radii (*a)* between 1×10^{-3} and 5.64×10^{-3} m (i.e. a circular defect area of 1 $\mathrm{cm^2}$);
- large circular defects having radii (*a)* between 0.5×10^{-1} and 3×10^{-1} m;
- hydraulic heads h_w ranging from 0.03 to 3 m;
- hydraulic conductivities of the soil component of the composite liner (GCL+CCL) k_s ranging from 1×10^{-10} to 1×10^{-8} $\mathrm{m\ s^{-1}}$ expressed as:

$$\frac{H_s}{k_s} = \frac{H_L + H_F}{k_s} = \frac{H_L}{k_L} + \frac{H_f}{k_f} \tag{2}$$

With H_L the thickness of the GCL (m), H_f the thickness of the CCL (m), k_L the hydraulic conductivity of the GCL (m/s) and k_L the hydraulic conductivity of the CCL (m/s).

- thickness of the soil layer component of the composite liner (GCL+ CCL) Hs ranging from 0.3 to 5 m.

Table 1. Existing empirical equations for assessing the flow rate through composite liners comprising a GMB and a GCL (and/or CCL) due to circular GMB defects

Defect	Contact conditions	N°: Empirical equations	Reference
Small circular defect	GCL-GMB	$3: Q = 2.10^{-4} h_w^{0.87} a^{0.07} k_s^{0.64} \left[1 + 0.31\left(\frac{h_w}{H_s}\right)^{0.79}\right]$	Touze-Foltz & Barroso (2006)
	Excellent	$4: Q = 0.096\ h_w^{0.9}\ a^{0.1}\ k_s^{0.74} \left[1 + 0.1\left(\frac{h_w}{H_s}\right)^{0.95}\right]$	Touze-Foltz & Giroud (2003)
Large circular defect	GMB-GCL	$5: Q = 0.116 h_w^{0.54}\ a^{0.4}\ k_s^{0.82} \left[1 - 0.22\left(\frac{h_w}{H_s}\right)^{-0.35}\right]$	Touze-Foltz & Barroso (2006)
	Excellent	$6: Q = 0.33\ h_w^{0.84}\ a^{0.18}\ k_s^{0.77} \left[1 - 0.1\left(\frac{h_w}{H_s}\right)^{0.027}\right]$	Touze-Foltz & Giroud (2005)

2.2 *Contact conditions*

Contact conditions express the characteristics of the interface between the GMB and the GCL. They correspond to the value of interface transmissivity (θ in $m^2.s^{-1}$) used to quantify the contact conditions as a function of the GCL hydraulic conductivity values. The contact conditions characteristics are based on experiments of flow rate measurements through GMB-GCL composite liners. Equations 7 and 8 present excellent contact condition and GMB-GCL contact condition. Excellent contact condition assumes a GMB without wrinkles on top of a soil component of a composite liner. It consists of a GCL installed on top of, and in close contact with, a low-hydraulic conductivity CCL (adequately compacted and presenting a very smooth surface). Furthermore, it is assumed that there is sufficient compressive stress to maintain the GMB in contact with the GCL and. In addition to that, Touze-Foltz & Barroso (2006) presented a contact condition expression especially for the GCL-GMB contact condition with a hydraulic conductivity of GCLs lower than 10^{-10} $m.s^{-1}$ as follows:

$$\log_{10}\theta = -1.7476 + 0.7155\log_{10}\ k_s \tag{7}$$

for excellent contact

$$\log_{10}\theta = -2.2322 + 0.7155\log_{10}\ k_L \tag{8}$$

for GMB-GCL contact

Bannour et al. (2015b) performed experiments aiming at quantifying advective flow rates in composite liners for which the GMB is damaged. This includes aged GCLs due to cation exchange and wet dry cycles and generally for GCLs for which hydraulic conductivity was greater than 10^{-10} $m.s^{-1}$. This has led to the development of new contact conditions for GMB-GCLs in the case of aged GCLs due to cation exchange and wet dry cycles and generally for GCLs which hydraulic conductivity was greater than 10^{-10} $m.s^{-1}$ expressed as follows in Equation 9:

$$\log_{10}\theta = -8.5965 + 0.1476\log_{10}\ k_L \tag{9}$$

3 METHODOLOGY OF ESTABLISHING EMPIRICAL EQUATIONS

3.1 *General overview of the methodology*

As explained by Touze-Foltz & Giroud (2003), the methodology for developing these equations consists of selecting a mathematical expression for the empirical equations (Eq. 1) and selecting values for the unknowns of the empirical equations. The flow rate calculated using the empirical equations must be as close as possible to flow rate rigorously calculated using the existing analytical solution. This was achieved by conducting numerical calculations defined by a wide range of values of the parameters. This includes contact conditions, defect type and size, soil layer thickness and hydraulic conductivity, and hydraulic head.

The values of the unknown exponents and factors in Equation 1, i.e. χ, ξ, κ, Cc, λ and μ, are determined by comparing the values of Q calculated using Equation 1 with the values of Q calculated using analytical solutions expressed by Equation 10 for circular holes as expressed in the following section.

3.2 *Mathematical expression of analytical solution for calculating flow rate through GMB-GCL composite liner*

For axysymetric defects the expression of the flow rate is given by Equation 10:

$$Q = \pi r_0^2 k_s \frac{h_w + H_s}{H_s} - 2\ \pi\ r_0 \theta\ \alpha\ [A I_1(\alpha r_0) - B K_1(\alpha r_0)] \tag{10}$$

Where: Q is the flow rate under steady-state conditions ($m^3.s^{-1}$), r_0 is the circular defect radius (m), k_s is the hydraulic conductivity of the liner (GCL + CCL) ($m.s^{-1}$), h_w is the hydraulic head (m), H_s is the thickness of the soil component of the composite liner (GCL + CCL) (m), θ is the interface transmissivity calculated using Equation 9 to take into account the GMB-GCL contact condition by taking into account the alteration by the environment of the GCL ($m^2.s$-1), $I_1$and K_1 are modified Bessel functions of the first order and α, A and B are parameters given by Equations 11 to 14:

$$\alpha = \sqrt{\frac{k_s}{\theta \, d_s}} \tag{11}$$

$$A = -\frac{h_w K_0(\alpha R) + H_s\left(K_0(\alpha R) - K_0(\alpha r_0)\right)}{K_0(\alpha r_0) I_0(\alpha R) - K_0(\alpha R) I_0(\alpha r_0)} \tag{12}$$

$$B = \frac{h_w K_0(\alpha R) + H_s\left(I_0(\alpha R) - I_0(\alpha r_0)\right)}{K_0(\alpha r_0) I_0(\alpha R) - K_0(\alpha R) I_0(\alpha r_0)} \tag{13}$$

As $A I_1(\alpha R) + B K_1(\alpha R) - H_s = 0$ (14)

Where K_0 and I_0 are modified Bessel functions of zero order and R is the radius of the wetted area at the interface between the geomembrane and the GCL.

Equations 10 to 14 apply to the boundary condition where the hydraulic head is equal to zero at a certain radius in the specimen, which in the present case is the cell radius according to experiments performed by Bannour et al. (2005b).

3.3 *Determination of unknowns of empirical equations*

The general methodology for determining exponents and factors gives a range of values for each exponent and factor. The parameter value is deduced graphically by representing each value as a function of the evolution of two others. The three steps of calculations consist determination of:

- the exponents χ, ξ, κ;
- the contact factor Cc;
- the factor λ and exponent μ.

The detailed methodology for calculating exponents and factors is given by Barroso (2005).

Calculations of the unknown exponents and factors were performed for each defect type (small circular defect, large circular defect) in order to determine new empirical equations by taking into account the contact condition for GCLs altered by their environment due to cation exchange and wet dry cycles. Calculations were performed by varying the following parameters: the defect area (*a*), the hydraulic head h_w and the hydraulic conductivity of the equivalent soil liner k_s (GCL+ CCL). Concerning analytical solutions, the interface transmissivity θ had been calculated using the contact condition for GCLs altered by their environment due to cation exchange and wet dry cycles (Equation 9).

4 RESULTS AND DISCUSSION

4.1 *Results and observations*

Figures 1 to 3 represent, respectively, the evolution of the exponents χ, ξ and κ of the hydraulic head h_w, the defect area dimensions (*a)* and the hydraulic conductivity of the equivalent soil liner k_s (GCL + CCL) as a function of the evolution of two others in the case of a small circular defects. Exponents χ, ξ and κ are evaluated by considering the average value of 0.91, 0.27 and 0.26 respectively plotted as a continuous line (Figs 1 to 3). The same methodology has been undertaken for the evaluation of the exponents χ, ξ and κ for the large circular defect.

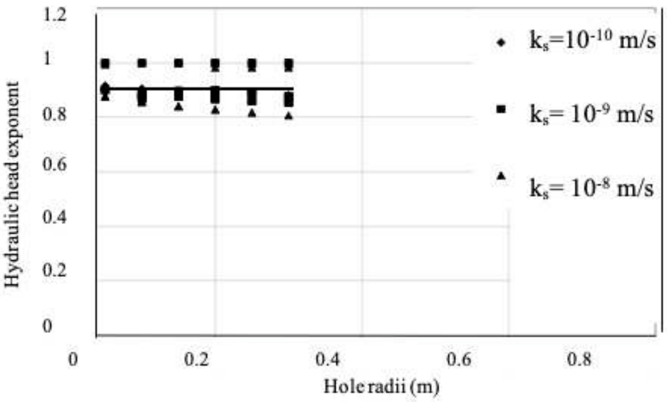

Figure 1. Visual determination of the hydraulic head exponent in the case of a small circular defect

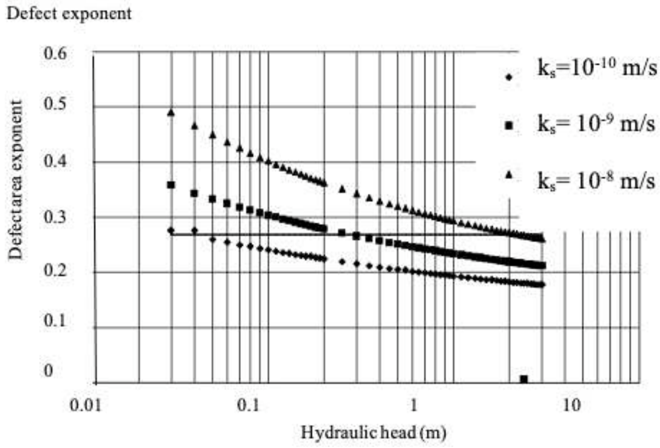

Figure 2. Visual determination of the defect area exponent in the case of a small circular defect

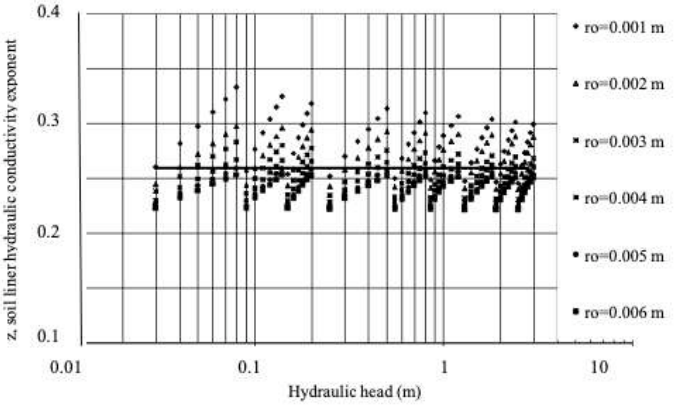

Figure 3. Visual determination of the soil liner hydraulic conductivity exponent in the case of a small circular defect

Table 2 presents the empirical equations obtained by calculations for the different circular defects considered in this study.

Table 2. Empirical equations proposed in this study obtained for small circular defect having diameters in the 2 to 20 mm range, for large circular defect having diameters in the 100 to 600 mm range

Defect	*Empirical equation*	*N°*
Small circular defect	$Q_L = 9.405 \times 10^{-8}\ h_w^{0.91}\ a^{0.27}\ k_s^{0.26} \left[1 + 0.34\left(\frac{h_w}{H_s}\right)^{0.68}\right]$	- *15*
Large circular defect	$Q_L = 3.03 \times 10^{-3}\ h_w^{0.65}\ a^{0.86}\ k_s^{0.64} \left[1 + 0.01\left(\frac{h_w}{H_s}\right)^{0.56}\right]$	- *16*

It could be noted that the exponents and coefficients obtained in equations presented in Table 2 are different from those obtained by Touze-Foltz & Barroso (2006) and Barroso (2005) who attempted to develop empirical equations exhibiting similar exponents and gradients for GMB-virgin GCL contact conditions for a given type of GMB defect. To analyse these differences, a comparative study was undertaken in order to review the discrepancy between new empirical conditions and conventional analytical solutions.

4.2 *Discussion: discrepancy of the new empirical equations developed and comparison with analytical solutions*

A comparative study between empirical solutions established in this study and empirical equations developed by Barroso (2005) and Touze-Foltz & Barroso (2006) for GMB-virgin GCLs contact condition has been undertaken. To perform this comparison, it is important to see the closest results to the analytical solution of flow rate for each set of parameters (defect dimension, hydraulic head and hydraulic conductivity of the equivalent soil liner).

To answer this question, more than 64,000 calculations were performed for the range of parameters presented in Section 2 and for each equation performed in this study presented in Table 1 and Table 2. The percentage of the number of cases studied corresponding to the number of calculations performed is plotted against the relative difference between the flow rates calculated using the analytical solution and Equations 3 and 15 in the case of a small circular defect in the GMB. As can be seen in Figure 4, for small circular defects, the flow rates rigorously calculated using the analytical solution given by Equation 9 and the approximate flow rates calculated using Equations 2 and 15 are different. 90% of the cases studied presented less than 60% relative difference for empirical Equation 15 established in this study compared to 300% for the relative difference calculation using Equation 2 with the analytical solution. As a result, Equation 15 established in this study by taking into account the GMB-GCL contact condition (Eq. 8) and the consideration of the alteration by the environment of the GCL is closer to the analytical solution (Eq. 10).

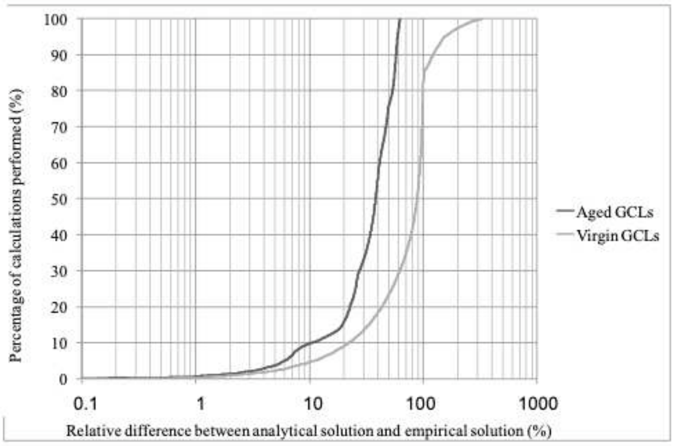

Figure 4. Relative difference between analytical solution and empirical equations developed in this paper for a small circular defect

Consequently, the empirical equation established in this study supplies design engineers with a tool to properly estimate the flow rate in the case when the GCL loses its hydraulic performance as a hydraulic barrier (i.e. by a combination of external site solicitations of cation exchange and wet dry cycles). Since the empirical equations are much simpler than the analytical solutions, they provide design engineers with a practical tool for evaluating flow rates through composite liners.

These empirical equations could be combined with diffusive flow rate equations to better estimate the flow rate pollutant through composite liners in bottom landfill barriers and potentially environmental consequences.

5 CONCLUSION

Knowing that practitioners are more familiar with empirical equations than analytical solutions for calculating flow rates through composite liners, this paper presented the development of empirical equations for calculation of the rate of liquid flow through circular defects (small and large) in the GMB component of composite liners involving GCLs altered by their environment. The alteration is due to cation exchange and wet-dry cycles and could lead to the increase in the hydraulic conductivity of the GCL and an increase in the leachate volumes penetrating the liner in few years.

This representation of composite liners in their operational use in landfill barriers by taking into account the evolution of the contact condition between the GMB and the GCL during the service life of the GCL could lead to more representative and realistic empirical equations for calculating the flow rate through GMB- GCLs composite liners. The important conclusions that could be deduced from this study are that:

- the GMB-GCL contact condition determined by taking into account the alteration by the environment has led to the development of new empirical equations for circular defects in the GM;
- empirical equations developed in this study are much closer to analytical solutions than previous empirical equations and can be used to improve estimating the flow rate though GMB-GCL composite liners compared to conventional equations (based on GMB-virgin GCLs) by taking into account combinations of external site solicitations (cation exchange and wet-dry cycles).

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