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Numerical experiment-artificial intelligence approach to develop empirical equations for predicting leakage rates through GM/GCL composite liners

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ABSTRACT

The aim of this study is to develop empirical equations to predict the liquid leakage rate through a composite liner comprising a geomembrane and a geosynthetic clay liner (GM/GCL) underlain by a free draining boundary and having a circular or a longitudinal defect in the geomembrane. For this purpose, an intensive numerical experimental program was conducted where different defect geometries and flow transport characteristics were studied to simulate most of the conditions likely to exist in practice in such type of composite liners. The results are presented in a dimensionless form to generalize the observed behaviour and to give more insight on the factors that control the leakage behaviour. Furthermore, the results are also used to develop empirical equations for predicting the rate of leakage. An artificial intelligent approach referred to as General Method of Data Handling (GMDH) was used for this purpose. The main advantage of the proposed leakage equations is their validity for different flow patterns as the effect of defects geometry and flow characteristics of the composite liner components are already embedded in the development of the equations. However, their validity is limited to the ranges of the dimensionless parameters that were used to develop them.

1. Introduction

Composite liner systems consisting of a geomembrane (GM) overlying a geosynthetic clay liner (GCL) and optional underlying layers (compacted clay liner, and/or an attenuation layer) are increasingly used in modern waste containment facilities (Bouazza, 2002; Rowe, 2005; Bouazza and Bowders, 2010). The purpose of using GM/GCL liners is to combine the advantages of the two materials, each having different hydraulic, physical and endurance properties so that contaminant migration can be limited to levels that will result in negligible impact. The GM has an important role under this configuration that is to serve as the primary barrier to contaminant migration since it is essentially impervious to flow when devoid of holes or defects.

However, it has been shown that defects in GMs can occur even with carefully controlled manufacture and damages can be found even in sites where strict construction quality control (CQC) and construction quality assurance (CQA) programs have been put in place (Bouazza et al., 2002, 2008; Rowe, 2005). Furthermore, wrinkles can also be developed in GMs during installation and when left exposed to solar radiation. Several studies have been conducted to understand how wrinkles form in GM, and how defects in wrinkles can form preferential contaminant flow paths and impact leakage rates through composite liners (Giroud and Morel, 1992; Rowe, 1998; Rowe et al., 2004; Rowe, 2005; Dickinson and Brachman, 2006; Take et al., 2007; Brachman and Gudina, 2008; Chappel et al 2012a,b; Rowe et al., 2012a,b; Take et al., 2012). In particular, Rowe (2005) indicated that a significant length of wrinkle(s) with a hole are needed to explain most observed leakages in the primary liner of double liner systems. Brachman and Gudina (2008), Dickinson and Brachman (2006) and Take et al. (2012) showed that wrinkles do not go away when the lining system is covered and loaded. Take et al. (2007), Chappel et al. (2012a,b), Rowe et al. (2012a,b) showed how extensive wrinkling can be formed depending on the time of installation. The study presented in this paper does not include the presence of wrinkles with defects and focusses solely on the case where GMs do not contain any wrinkles and are in direct contact with the GCL.

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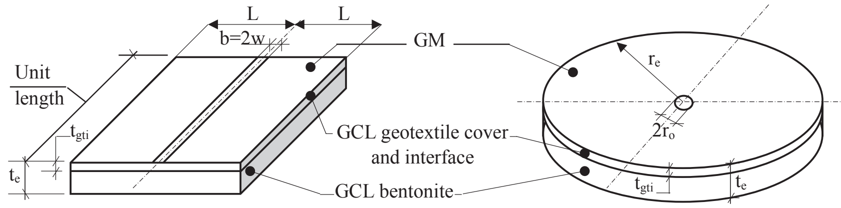
Table 1
The proposed GMDH leakage equations.

Defect type	Longitudinal defect	Circular defect
Geometry		
Leakage flow rate equations	Leakage flow rate per unit length: $Q_l = F_l k_e^s bh$ $(k_e^s)^{-1} = (t_r)k_{gti}^{-1} + (1-t_r)k_{bt}^{-1}$ $k_{gti} = k_{gt} \times 10^{Cn}$ $t_r = t_{gti}/t_e$ h: the total head drop across the GCL geotextile cover and bentonite k_{bt}: hydraulic conductivity of GCL bentonite k_{gt}: hydraulic conductivity of GCL geotextile cover k_{gti}: hydraulic conductivity of GCL geotextile cover and the interface C_n: interface contact condition, $C_n = 0, 1, 2$ for excellent, good, and poor contacts, respectively $F_l = \frac{100}{\left(0.08237133\frac{(\lambda+1)}{2}+0.007905793\right)^2}$ $\lambda = -0.274508037894264$ $-1.000595417839361\alpha_1$ $+0.5427966606363697Y\alpha\alpha_3$ $+0.4122259654000215\alpha_1^2$ $+0.1726394427024338\alpha_2^2$ $-0.2280766384859098\alpha_1^3$ $-0.7950747012405668\alpha_1\alpha_2$ $-0.9726687760368563\alpha_1\alpha_3$ $+0.4106332726589392\alpha_2\alpha_3$ $-0.7833411843849682\alpha_1\alpha_2\alpha_3$ $\alpha_1 = \left(\frac{1}{3}\right)\log\left(\frac{k_{gti}}{k_{bt}}\right) - 1$; $\alpha_2 = \frac{2(\beta_1-0.69897)}{1.50515} - 1$; $\alpha_3 = \frac{2(\beta_2-0.021875)}{1.978125} - 1$ $\beta_1 = \log\left(\frac{L}{w}\right)$; $\beta_2 = \left(\frac{w}{t_e}\right)$	Leakage flow rate: $Q_c = F_c k_e^s r_o h$ $F_c = \frac{1}{\left(0.4732529\frac{(\lambda+1)}{2}+0.01411734\right)^2}$ $\lambda = -0.05892850385824019\alpha_3$ $-0.2356667664632166\alpha_1$ -0.9003312477094435 $-0.2191734377530577\alpha_2$ $+0.6757618058353562\alpha_1^2$ $-0.457727701188876\alpha_1^3$ $+0.09148612409257305\alpha_2^2$ $+0.07349427256028553\alpha_1\alpha_3$ $-0.2098572544839747\alpha_1^2\alpha_3$ $+0.1421469485894003\alpha_1^3\alpha_3$ $\beta_1 = \log\left(\frac{r_e}{r_o}\right)$; $\beta_2 = \left(\frac{r_o}{t_e}\right)$

Several experimental studies were carried out to investigate the factors affecting the leakage rate through a damaged GM and included the effect of defect geometric characteristics, and the flow transport properties of the underlying liner material (Fukuoka, 1986; Brown et al., 1987; Walton et al., 1997; Cartaud et al., 2005a; Chai et al., 2005; Barroso et al., 2006; Rowe and Abdelatty, 2013). Furthermore, analytical and empirical equations were also developed to assess the liquid leakage rate through composite liners having a defect in the GM. The analytical solutions for the leakage problem through a composite liner dates back to Fukuoka (1986), Brown et al. (1987), and Jayawickrama et al. (1988) and the work conducted by Rowe (1998) and Touze-Foltz et al. (1999). Fundamentally, the developed analytical leakage equations assume a predefined unidirectional flow pattern where the leakage flows radially or horizontally along the interface between the GM and the GCL and then flows vertically through the GCL (Touze-Foltz et al., 1999). However, Foose et al. (2001) have shown that this is not the only flow pattern that the composite liner could experience as the transport properties of the composite liner components (GCL, and interface zone) have a direct effect on the configuration of the developed flow patterns taking place during the leakage process.

Several versions of empirical equations were proposed by Giroud and Bonaparte (1989), Giroud et al. (1989), Giroud (1997), Touze-Foltz and Giroud (2003), 2005, Giroud and Touze-Foltz (2005) and Touze-Foltz and Barroso (2006). The empirical equations are preferred by practitioners since the analytical equations are rather complex (Touze-Foltz and Barroso, 2006). The available empirical equations inherited the limitation of the analytical equations as they were developed and validated under the framework of the analytical equations (Brown et al., 1987; Touze-Foltz et al., 1999). Furthermore, these empirical equations were developed for the case of composite liners having thickness varying between 0.3 m and 5 m, and a liquid head on top of the GM between 0.03 m and 3 m. These composite liners comprised either GM on soil liners (Touze-Foltz and Giroud, 2003) or GM/GCL on soil liners (Touze-Foltz and Barroso, 2006). Thus, they were not developed to deal with the case of thin composite liners which comprise GM/GCL underlain by free draining boundary (the subject of this study).

The aim of this study is to develop empirical equations to predict the liquid leakage rate through a GM/GCL composite liner underlain by a freely draining layer and having a circular or longitudinal defect in the GM. The originality of this study rests on the fact that it considers the GCL as a multi-layered composite material, and that the developed equations are valid for the whole range of the flow pattern configurations that could develop when a leakage occurs. Furthermore, a novel numerical experiment-artificial intelligent approach was used to develop these empirical equations.

2. Problem configuration

This paper focuses on leakage through a thin composite liner comprising a GM underlain by a saturated GCL and having a circular or longitudinal defect in the GM. The radius of the circular defect in the GM is referred to as r_0 whereas the width of the longitudinal defect in the GM is referred to as $b = 2w$ as shown in the geometry section of Table 1. It is assumed that the composite liner is both overlain and underlain by a highly permeable medium. The GCL consists of a bentonite layer contained between two geotextile layers. As the cover geotextile layer is expected to hold a higher conductivity than the bentonite layer and could make up to nearly