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Field and laboratory observations of down-slope bentonite migration in exposed composite liners☆

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A B S T R A C T

GCL manufacturers recommend that composite liners (i.e., a geomembrane (GMB) over geosynthetic clay liner (GCL)) be covered in a timely fashion. This paper highlights the importance of following this recommendation by reporting on significant down-slope bentonite migration first noted at the Queen's University Environmental Liner Test Site (QUELTS) constructed in 2006 (QUELTS I). The down-slope erosion is attributed to thermal cycles that caused evaporation of moisture from the GCL on sunny days (when the black geomembrane heated to 60–70 °C) followed by condensation of moisture on the underside of the geomembrane at night when the geomembrane cooled. The condensed moisture would drip onto the GCL and run down-the slope. Repetition of this process over an extended period of time caused the erosion of bentonite at some locations in all four GCLs examined in the 3.7 years the liner was exposed before the full inspection of the GCL which detected the mechanism. A series of laboratory experiments confirmed that dripping of evaporative water could cause down-slope erosion in relatively few cycles. These tests also identified several GCL products with a high resistance to down-slope erosion prompting the desire to construct a second field study to examine the issue. Thus, in 2012, the liner system was removed and QUELTS II was constructed with a new series of 7 composite liners. This paper highlights the key findings from these studies with particular emphasis on issues of importance to designers, regulators and installers.

1. Introduction

Composite liners (i.e., a geomembrane (GMB) over geosynthetic clay liner (GCL)) have been widely and successfully used in landfills over the past 20 years and are now being increasingly used in large mining (e.g., heap leach) applications (e.g., Rowe, 2005, 2012, 2014; Hosney and Rowe, 2014; Liu et al., 2014, 2015; Bouazza et al., 2015; Rouf et al., 2015). GCL manufacturers recommend that composite liners be covered in a timely fashion. Nevertheless, liners are often left exposed for weeks to years; especially on side slopes. This has the potential to cause panel shrinkage of some GCLs as first reported by Thiel and Richardson (2005) and Koerner and Koerner (2005), and subsequently examined in the laboratory by Thiel et al. (2006), Bostwick et al. (2010) and Rowe et al. (2010, 2011a).

The Queen's University Environmental Liner Test Site (QUELTS) was first constructed in 2006 (QUELTS I; Brachman et al., 2007) to examine wrinkling of the geomembrane and allow the comparison of the effect of smooth and textured black high density polyethylene (HDPE) GMBs and shrinkage of four different commonly used GCLs when left exposed as part of a full scale composite liner under nominally identical conditions. After completion of the wrinkle study (Rowe et al., 2012; Chappel et al., 2012a,b), the liner was opened to conduct a full survey of panel movements due to shrinkage (Brachman et al., 2014a). At this time, significant down-

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slope erosion of bentonite due to moisture migration was observed (Take et al., 2015a,b; Rowe et al. 2014a). This in-plane erosion was quite different to the erosion that can occur when a GCL resting on a foundation layer which is not a suitable filter is permeated normal to the plane of the GCL, as examined by Rowe and Orsini (2003).

Down-slope bentonite erosion had not previously been reported in the literature although the accumulation of bentonite at the bottom slopes has been reported in some consulting reports and by Stark et al. (2004) suggesting, in hindsight, that it had occurred but not been recognised in previous field investigations. To provide some insight into the factors affecting down-slope bentonite erosion, a laboratory technique was developed for investigating the effect of dripping evaporative water on GCLs (Ashe et al., 2014, 2015; Rowe et al., 2014b). These experiments identified several GCL products with a high resistance to down-slope erosion, prompting the desire to construct a second field study to examine the issue. Thus, in 2012, the liner system was removed and QUELTS II was constructed with a new series of 7 composite liners (Brachman et al., 2014b; Rowe et al. 2014a, 2016).

The objective of this paper is to draw together the findings from the field and laboratory studies of down-slope bentonite erosion that have been conducted and to summarize the key findings from these studies with particular emphasis on issues of importance to designers, regulators and installers.

2. QUELTS I

2.1. The site

The Queen's Environmental Liner Test Site (QUELTS) is located 40 km north-northwest of Kingston, Ontario, Canada, at latitude of 44°34′14″N and longitude of 76°39′44″W (Brachman et al., 2007). A 46 m wide (north-south) and 80 m long embankment was constructed with its long axis oriented in the east-west direction. The silty sand (based on dry sieving) embankment fill was taken from adjacent borrow pits and compacted to its original *insitu* density at its natural water content. The north and south slopes were constructed at 3H:1V (18.4°) with a 5-m-wide flat crest. On the 20 m north facing slope, four GCL products (GCL1-4, Tables 1–3) were placed with one type of GCL in each of the six adjacent sections with three panels of GCL each overlapped by 300 mm in each section (GCLs in the sections from west to east: GCL2, GCL1, GCL2, GCL3, GCL4, GCL3). All the GCLs on the north slope were quickly covered by 0.7 m of cover soil.

A composite liner involving a GCL covered by a black 1.5 mm high density polyethylene (HDPE) geomembrane was installed on both the 22 m south facing slope (168° azimuth) and the 20 m base which had a gentle 3% slope to the south (Figs. 1 and 2). There were a total of six sections, each with three GCL panels running from the anchor trench at the top of slope, down the slope, across the base, and terminating in an anchor trench at the south end of the base. From west to east, the sections [#] were as follows (Fig. 2 and Tables 1–3; Take et al., 2015a): [1] GCL2 (white nonwoven geotextile facing up), [3] GCL3 (black woven geotextile facing up; denoted as 3a in Fig. 2), [3] GCL2 (white nonwoven geotextile up), [4] GCL4 (black nonwoven geotextile up), [5] GCL1 (off-white woven geotextile up), and [6] GCL3 (white nonwoven geotextile up; denoted as 3b in Fig. 2). No trial was conducted with the scrim reinforced nonwoven of GCL2 facing up. The east and west sections of the slope and the base were covered with smooth 1.5 mm HDPE geomembrane. The central four sections of the slope were covered with textured 1.5 mm HDPE geomembrane. The composite liner was installed on 10–12 September 2006 and subsequently left exposed.

2.2. The mechanism for down-slope bentonite migration and erosion

Once placed and covered, a GCL takes up water from the underlying soil (Rayhani et al., 2011; Chevrier et al., 2012; Rowe, 2014). However, on sunny days the geomembrane, especially a black geomembrane, will be heated by solar radiation to temperatures of 60–70 °C (~40 °C above ambient temperature near midday on a sunny day) at QUELTS. The solar radiation reaching the geomembrane will depend on (Take et al., 2014; Take et al., 2015b; Rowe and Ewais, 2015): the site latitude, slope, orientation with respect to the sun, time of year, and weather conditions (especially cloud cover). Heating of the geomembrane has two effects, as discussed below.

First, as the geomembrane temperature increases there is significant thermal expansion and buckling of the geomembrane (e.g., Giroud and Morel, 1992; Pelte et al., 1994; Take et al., 2012) to form a large network of interconnected voids below the wrinkles in the exposed geomembrane (e.g., Rowe et al., 2004; Giroud, 2005; Take et al., 2007; Rowe et al., 2012; Chappel et al., 2012a,b). Fig. 3 shows the wrinkling on the western half of the slope (far-right geomembrane seam in Fig. 3a marks the middle of the embankment). Due to the blown-film method of manufacture, the geomembrane had creases running parallel to the roll direction that are located about 1.7 m from each edge of the roll (i.e., spaced at about 3.4 m). These creases are small enough to be essentially unnoticeable as the geomembrane comes off the finished roll but are sufficient to initiate wrinkling when the geomembrane undergoes thermal expansion. These "crease wrinkles" have a "peaked" shape (Fig. 3b) and, since they occur at the creases, they run parallel to the roll direction. Since the rolls were placed from top to bottom of the slope, the wrinkles observed on the slope at QUELTS included regularly spaced down-slope crease wrinkles (Fig. 3a). In addition,

Table 1
Properties of GCL products tested. All GCLs were needle-punched with a nonwoven (NW) cover geotextile (GTX); based on Rowe et al. 2016.

Generic Identifier[a]	Used at QUELTS	Panel width (m)	Carrier GTX[b]	Thermally treated	Up[b] as-placed	Sodium bentonite type
GCL1	I	4.72	W	Yes	W,carrier up	Fine granular
GCL2	I & II	4.72	SRNW	Yes	NW, cover up	Fine granular
GCL3	I	4.72	W	No	3a: W carrier up 3b: NW, cover up	Coarse granular
GCL4	I	4.72	NW	No	NW, cover up	Coarse granular
GCL5	II	4.85	SRNW	Yes	NW, cover up	Powdered
GCL6	II	4.85	W	Yes	NW, cover up	Powdered
GCL7	II	4.72	SRNW	Yes	NW, cover up	Fine granular, polyacrylamide enhanced
GCL8	II	4.72	W, PP	Bonded by PP	W, PP, carrier up	Fine granular

[a] Generic identifiers are the same as used in a laboratory study of 10 GCLs reported by Ashe et al. (2014) to allow direct comparison of results in that study with those obtained in this and the earlier field study.
[b] W = (slit-film) woven; NW = (needle-punched) nonwoven; SR = (slit-film) scrim-reinforced; PP = polypropylene coating.