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

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ABSTRACT

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.

Table 2
Initial properties of GCL products tested at QUELTS (modified from Rowe et al. 2016).

Generic identifier	Average dry mass of GCL[a] (g/m^2)	Range of dry mass (g/m^2)	Average dry mass of cover geotextile[a] (g/m^2)	Average dry mass of carrier geotextile[a] (g/m^2)	Average dry mass of bentonite[a] (g/m^2)
GCL1[b]	4968 ± 93	–	242	123	4603
GCL2	4256 ± 182	4007–4478	226	252	3778
GCL3[b]	5640 ± 422	–	283	125	5232
GCL4[b]	4830 ± 188	–	264	233	4333
GCL5	5114 ± 83	4971–5182	282	395	4437
GCL6	5045 ± 423	4703–5517	190	142	4714
GCL7	4977 ± 216	4677–5171	202	238	4538
GCL8	4179 ± 229	3927–4491	219	378	3582
ASTM	D5993	D5993	D5261	D5261	D5993

[a] Average ± standard deviation of five duplicate virgin GCL samples each 100 mm × 100 mm, taken from same area of GCL roll.
[b] Values measured by Bostwick (2009).

Table 3
Initial properties of GCL products tested at QUELTS (modified from Rowe et al. 2016).

Generic identifier	Swell index[a] (mL/2 g)	w_{ref}[b, c] [at 2 kPa; distilled water, 1 month hydration] (%)	Average peel strength[d] (N/m)	Maximum peel strength (N/m)	Average peak peel force[d] (N)
GCL1[e]	26 ± 1	150	662 ± 88	800	94 ± 17
GCL2[f]	32 ± 1	144 ± 4	1549 ± 75	1638	194 ± 16
GCL3[e]	23 ± 1	210	1510 ± 256	1750	204 ± 36
GCL4[e]	22 ± 1	190	1780 ± 280	2000	219 ± 30
GCL5	34 ± 1	152 ± 5	1621 ± 140	1822	287 ± 33
GCL6	35 ± 1	132 ± 7	703 ± 72	782	113 ± 14
GCL7	35 ± 1	131 ± 5	1326 ± 65	1394	180 ± 20
GCL8	31 ± 1	124 ± 10	1516 ± 108	1685	204 ± 16
ASTM	D5890		D6496	D6496	D6496

[a] Average of duplicate tests on samples extracted from the start and end of each panel installed on site.
[b] Average of six replicates from the same hydrated virgin GCL sample, each 100 mm × 100 mm.
[c] Following Rayhani et al. (2011), w_{ref} represents the maximum water content a GCL will hydrated to under a given stress.
[d] Average of five duplicate virgin GCL samples each 100 mm × 200 mm, taken from same area of GCL roll.
[e] Values measured by Dr. M. Hosney [at 2 kPa; distilled water, 1 month hydration].
[f] GCL2 values reported are from product rolls installed at QUELTS II.

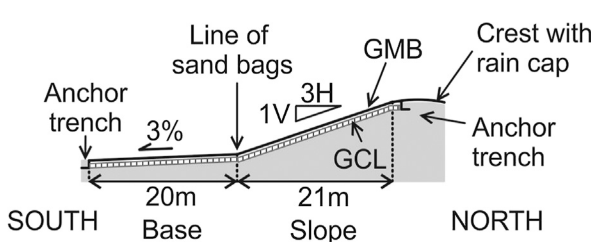

Fig. 1. North-south cross section at QUELTS.

there were many cross-slope wrinkles. Some of the cross-roll wrinkles were inclined to the horizontal (Fig. 3a) and most intersected a down-slope wrinkle and/or a seam (potential drip accumulation and drop points). There were also many smaller wrinkles intersecting either down-slope creased wrinkles or seams that also were smaller sources of evaporative water.

Second, heating of the GCL below the geomembrane causes water to evaporate from the GCL and accumulate in the void space below the geomembrane wrinkles. Take et al. (2015b) indicated that the temperatures at wrinkles could be 15 °C higher than other locations where there was close contact between geomembrane and GCL. As the solar radiation decreases later in the day, the geomembrane temperature will decrease to below that in the air space. Water vapour will then condense as distilled water on the

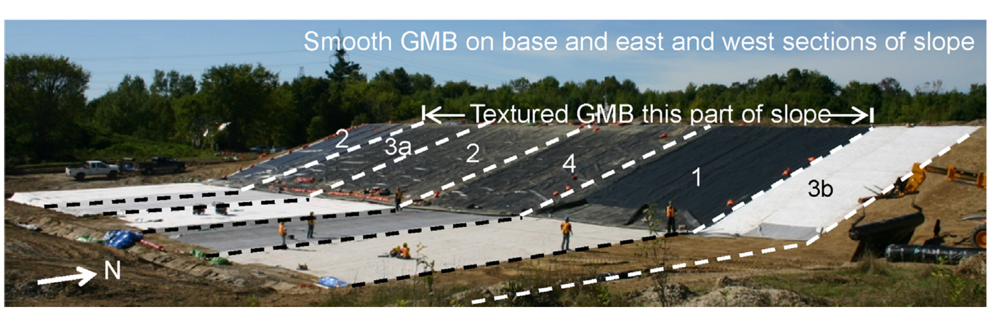

Fig. 2. QUELTS I during construction showing GCL and geomembrane layout. Each section had 3 panels of GCL. Sections (west to east): GCL2, GCL3a, GCL2, GCL4, GCL1 and GCL3b. The total lined width was 80 m.

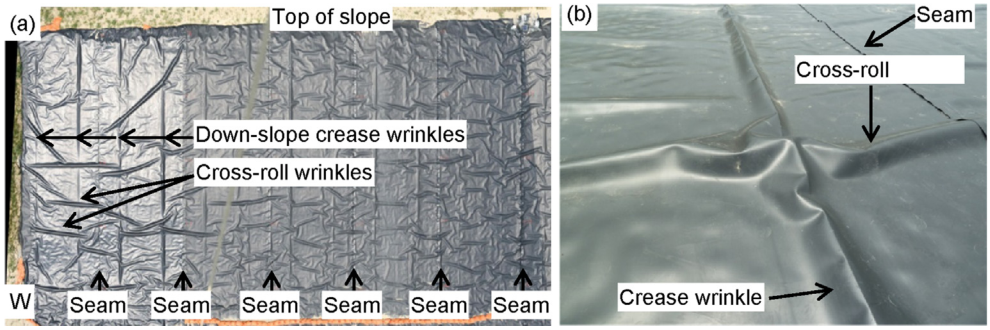

Fig. 3. Wrinkling: (a) Aerial view of western half of slope at 12:30 on 26/7/07, and (b) Winkle intersection.

inclined colder geomembrane surface where droplets will form and flow down the underside of the geomembrane until they collect at a drop point. A drop point may be a slight irregularity in the foundation, the intersection of wrinkles (Fig. 3), the end of a wrinkle, or where a wrinkle intersects the flap on the underside of a geomembrane weld. The distilled water will localise and accumulate until the drop is large enough to drip onto the GCL at these specific locations, and form rivulets running down the surface of the GCL (Fig. 4a) which can then transport bentonite to the base (Fig. 4b). The next section will examine the effect of this condensed evaporated water on the GCL.

2.3. *Field observations of down-slope bentonite migration and erosion*

To avoid affecting the wrinkle study (Rowe et al., 2012), which was one of the two primary motivations for the construction of QUELTS I, there was no opportunity to inspect the GCLs except for a few spot checks at the GCL panel overlaps for the first 3.6 years following construction. During this period: (a) spot checks at the locations of the panel shrinkage monitors showed some rivulet formation (Fig. 4a), (b) water ponding was noted at the bottom of the slope, and (c) a change in the wrinkling pattern on the base of the slope with time was observed. However, there was nothing observed that clearly signalled that down-slope bentonite erosion had occurred.

At the end of the wrinkle study, the geomembrane was opened at each section to allow measurement of panel shrinkage. When the first (western-most) slope section was opened very white streaks were observed on the up-facing nonwoven cover GCL (Fig. 5). Tactile inspection suggested that there was little or no bentonite remaining between the GCL cover and carrier geotextiles in many of these zones. A 0.61 m wide by 1.52 m long section near the bottom of the slope was removed, replaced with new GCL (bottom centre of Fig. 5), and brought back to the laboratory for X-ray and physical study where the absence of bentonite was confirmed and quantified (Take et al., 2015a). When the base was opened, it was found that at many locations, the geomembrane was adhering to the GCL due to bentonite that had accumulated on the base and dried. Although areas where erosion may have occurred were apparent from a normal visual inspection (without the backlight technique developed for QUELTS II) for the GCLs with a white nonwoven geotextile facing up (GCL2 and GCL3b), this was not the case for the other sections where it was very difficult to see where erosion had occurred from normal visual inspection. For these sections, the considerable accumulation of bentonite at the base of each slope (Fig. 4b) suggested that down-slope bentonite erosion had occurred but the locations of bentonite streaks on the GCL surface generally did not correspond to locations of erosion. At these sections, a tactile inspection was required to identify locations where bentonite had been largely eroded leaving just the cover and carrier geotextile. Samples were taken at the bottom of the slope (and replaced with new GCL similar to indicated above for western GCL2 slope section) for laboratory study. Each section was resealed, the welds tested, and left for another year while the laboratory investigation was conducted.

In early June 2011 (4.7 years after construction), the QUELTS I experiment was terminated with a detailed inspection of each GCL panel. Fig. 5 shows GCL2 at the western most slope section. For this GCL, likely areas where the bentonite had been washed out (eroded) were signalled by a whiter colour than the surrounding GCL. Since not all white areas were totally eroded, tactile inspection was used to confirm that an area had little to no bentonite remaining. Areas identified as having essentially no remaining bentonite were highlighted in orange paint to facilitate photography (Fig. 5). The primary erosion feature ran from the top to the bottom of the slope at the location of the western-most seam shown in Fig. 3a. Inspection of Fig. 3a shows many small and some

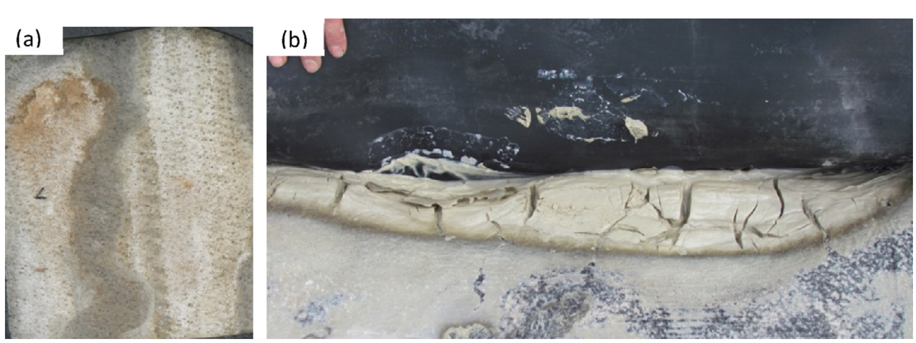

Fig. 4. (a) Rivulet meandering down-slope, and (b) accumulation of bentonite at base of GCL3a slope.

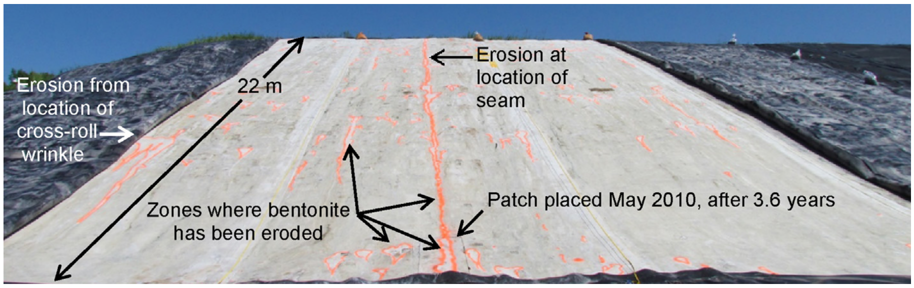

Fig. 5. GCL2 – Western-most section in June 2011 after 4.7 years on 3H:1V south facing slope. Significant downslope-bentonite erosion was observed at all areas highlighted with orange marking paint. Modified from Brachman et al. (2014b). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

large wrinkles converging on the seam. It appears that water which condensed in these wrinkles migrated to the seam and that the seam acted as a drop-point causing water to accumulate and run down the GCL below the seam. This erosion feature was first observed when the section was opened in May 2010 and a portion was removed and replaced as discussed above. In the subsequent year, the replacement patch had also experienced substantial erosion (bottom centre of Fig. 5) indicating that substantial erosion could occur at this site in as little as one year. This feature was typically 90 mm wide but was 330 mm wide at a location where a major angled cross-roll wrinkle intersected the seam (Fig. 3a). Another significant feature was observed near the west of the first panel at the location of a cross-roll wrinkle (Fig. 5) with a long downward extension which was located below a portion of the westernmost down-slope crease wrinkle (Figs. 3a and 5). In total, 127 erosion features were detected for this one section (a feature being defined as essentially complete erosion of bentonite over a width exceeding 15 mm).

Like the western section, the third section was also constructed with GCL2 (Fig. 2) but whereas the western-most section [1] was covered by smooth geomembrane, in section [3] it was covered with textured geomembrane. Comparison of the two sections indicted very similar behaviour and erosion patterns. Thus, texturing did not have any apparent effect on the erosion of GCL2 (Take et al., 2015a). Again there was a primary linear erosion feature associated with the geomembrane seam (the seam second from the right in Fig. 3a) and other longer features associated with down-slope crease wrinkles.

To examine the effect of the type of geotextile facing up, GCL3 was placed with the white nonwoven cover facing up at the eastern-most section [6] (GCL3b; Fig. 2) and with the black woven up at section [2] (GCL3a; Fig. 2). When the white nonwoven was placed up, it was relatively easy to identify the locations of possible erosion features by tactile inspection (Fig. 6). The erosion was very similar to that observed for GCL2 (Fig. 5). Once again the main linear erosion feature is at the location of a geomembrane seam (Take et al., 2015a). Other significant down-slope linear features generally aligned with down-slope creased wrinkles. However, a number of features also aligned with a local minor high spot in the foundation.

When GCL3a was placed with the black woven upwards, it was not possible to see areas of potential erosion by simple visual inspection in daylight. As indicated by Ashe et al. (2015) and discussed later, it was even challenging to identify a zone where the bentonite had been eroded with a bright light beneath the GCL because of the colour. Thus, for this GCL, the search for erosion relied on a tactile inspection to identify possible erosion features and cutting of the upper geotextile to confirm any significant absence of bentonite at these locations. Because the features were more difficult to detect, the field investigation was intended to confirm whether significant erosion occurred (which it did), rather than precisely quantifying the entire extent and frequency of features for this configuration. Thus, the number of erosion features identified in this manner was only about 25% of those identified for the GCL placed with the white nonwoven facing up. Considering the findings from the spot check for GCL4 and the laboratory study discussed later, this difference is probably due to the difficulty of finding features smaller than extensive erosion by tactile inspection (and even they could be missed on a large surface). Although many erosion features were probably missed, sufficient large and hydraulically significant features were identified to conclude that the GCLs effectiveness as a hydraulic component of a composite liner had been compromised after 4.7 years of exposure (Take et al., 2015a).

GCL1 was also placed with a woven carrier geotextile facing upwards. This woven geotextile was off-white rather than the black of GCL3, but it was still difficult to visually identify erosion features and reliance again was placed on a tactile inspection and cutting of

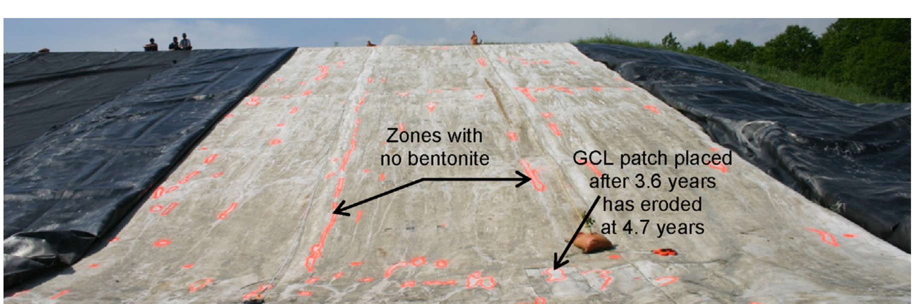

Fig. 6. GCL3b placed with white nonwoven cover facing up in June 2011 after 4.7 years on 3H:1V south facing slope. Areas of significant bentonite erosion highlighted.

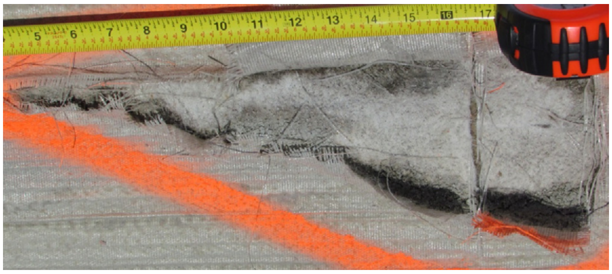

Fig. 7. Erosion feature identified by tactile inspection and then destructively inspected to confirm bentonite loss. Photo has been rotated 90°. 140 mm wide loss of bentonite at right of photo was upslope and the feature narrowed over its 420 mm length running down the slope (right to left).

the GCL at areas of potential erosion (Fig. 7). In this case, the number of erosion features identified was about 30% of that found with the white nonwoven cover of GCL2 facing upward. Nevertheless, as for GCL3a with the woven up, GCL1 had sufficient significant eroded features (the largest being about 200 mm wide and 1000 mm long) that, after 4.7 years of exposure, would compromise its effectiveness as a hydraulic component of a composite liner. The fact that it was much more difficult to identify erosion features with the off-white woven up than with the nonwoven white geotextile up was curious. The laboratory investigation described in Section 3.3 below provides insight into this matter.

GCL4 was placed with a black nonwoven facing up making it much more difficult to visually identify potential erosion features than was the case for GCL2 which has a similar (other than for colour) needle-punched geotextile facing up. Thus, again, it is highly probable that some erosion features in GCL4 were undetected. Take et al. (2015a) attempted to quantify the difficulty, by taking a section across one panel after it has been subjected to tactile inspection for erosion features and then cut the entire section to identify the presence/absence of bentonite and found about twice as many erosion features 25 mm or more in width than were identified by tactile inspection. Despite this difficulty, 70 erosion features were detected by tactile inspection with the largest feature detected being about 500 mm wide and 1500 mm long. The dark background highlighted the light grey areas where bentonite had been transported and then deposited on the GCL (Fig. 8). These bentonite streaks were fairly uniformly distributed over the GCL but were not necessarily correlated with the location of erosion features (Take et al., 2015a).

Many more erosion features were detected on the slope than on the base for all sections. Nevertheless, the base was not free of erosion features. The most extreme case was on one panel of GCL4 where two significant features without bentonite were detected. One was 18 m long and 25–50 mm wide (Fig. 8) while the other was 560 mm long and 75 mm wide. Similar erosion features were reproduced on a 3% slope in the laboratory (§3.3.4) confirming the field observation that down-slope erosion can occur on a relatively shallow slope and hence with a relatively low velocity.

2.4. *Question arising from QUELTS I*

The unexpected discovery of significant bentonite erosion on the slope and, while still significant but to a lesser extent, on the base of QUELTS I raised many questions including: (i) could the mechanism be simulated in the laboratory? (ii) what factors affect the occurrence of down-slope erosion? (iii) how long would it take for an erosion hole to develop in the GCL? (iv) are there better ways of identifying erosion features for GCLs with a black geotextile facing upwards? (v) why was it more difficult to identify erosion features with the off-white woven up than with the white nonwoven up? and, (vi) are there means of mitigating the erosion observed at QUELTS I? In an attempt to address these questions, an extensive laboratory study was initiated and then QUELTS II was constructed as summarized in the following sections.

3. Insights from laboratory studies

3.1. *Identification and classification of erosion features*

Visual identification of erosion features is highly dependent on lighting conditions and the type of GCL as discussed above for QUELTS I. At the termination of the QUELTS I experiment (4.7 years), erosion was confirmed by destructively cutting the GCL and inspecting for bentonite between the cover and carrier geotextiles (Figs. 7 and 8, Take et al., 2015a; Rowe et al. 2014a). To be able to confirm erosion without the need for destructive testing, a technique for backlighting was developed for use in the laboratory and the field at QUELTS II (as described later). However, in the field, backlighting was reserved for suspected zones of erosion and as spot checks because it was not practical to inspect all locations on

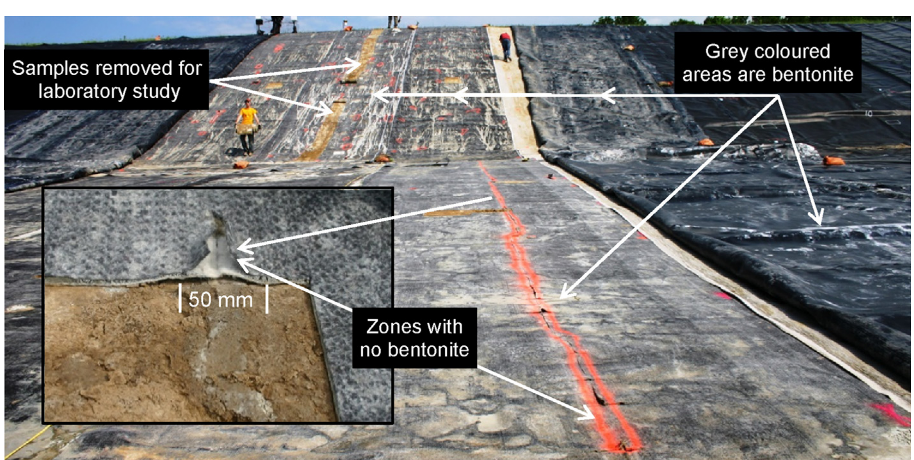

Fig. 8. GCL4 on the 3% sloping base in the foreground (showing that, given enough time, erosion can occur even on a small slope) and on the 3H:1V slope in the background. After 4.7 years, an extensive (18 m long) zone with no bentonite is highlighted on the right-hand base panel. Light grey areas are bentonite deposited on the black geotextile or adhered to the bottom surface of the geomembrane.

the GCL in a full scale field setting. The target zones for a backlit inspection in the field at QUELTS II were still identified visually and/or by a gentle tactile inspection.

The investigation at QUELTS I highlighted the need to develop a system for classifying different levels of bentonite erosion (Ashe et al., 2014, 2015; Brachman et al., 2014b). Erosion appeared to be initiated at desiccation cracks in bentonite that had hydrated sufficiently to form a gel and then dried and desiccated. If water then drips onto the cracked GCL and runs down a crack, it has the potential to remove bentonite before the gel is re-established. The first stage of the erosion process is when there has been some thinning of the bentonite; this was classified as onset erosion ('o'). With further flow and loss of bentonite, a gap develops that, with appropriate backlighting, was visible at the end of the hydration phase of the laboratory test, to be described below or when inspected in the field. If this gap had a width less than 15 mm, it was classified as early erosion ('e'). When the width of this gap was between 15 and 25 mm, the feature was classified as erosion ('E'). When the width of the gap exceeded 25 mm over a length less than 300 mm, the feature was classified as irrecoverable erosion ('EE') and when the width exceeded 25 mm over a length of greater than 300 mm was classified as irrecoverable extreme erosion ('EEE'). This nomenclature will be used to describe erosion features in the following sections.

3.2. Laboratory simulation of down-slope erosion

Ashe et al. (2014) described the development of a laboratory test for simulating down-slope bentonite erosion (Fig. 9). For a composite liner on moist subsoil that is left exposed in the field, there is likely to be a period of moisture uptake by the GCL followed by drying on a hot sunny day which would give rise to the desiccation cracks observed in samples recovered from the field at QUELTS I (Take et al., 2015a). To simulate this in a laboratory experiment, GCL specimens (350 mm wide by 550 mm long) were hydrated to a target gravimetric water content of 100%, left to homogenize with no confining load, and were then dried in an oven at 60 °C for 15 h. The specimens were placed on clear Perspex trays inclined at 3H:1V (unless otherwise noted) and clamped along the top edge. Water was then allowed to drip at a prescribed rate (deionised water at 3 L/h unless otherwise noted) from a height of 50 mm above the GCL at the center line of the specimen just below the restraint. The water was collected along the bottom edge of the tray. An erosion experiment involved dripping water onto the GCL for 8 h (referred to as the hydration phase) followed by 16 h when the GCL was allowed to air dry at room temperature (~20 °C). This cycle was repeated until the end of the experiment. At the end of the hydration phase, a light was briefly placed below the tray while photographs were taken (Fig. 10). The bentonite loss per cycle was quantified by monitoring bentonite in the outflow.

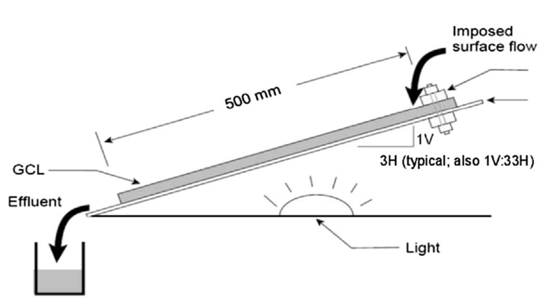

Fig. 9. Schematic of apparatus used in Ashe et al. (2014, 2015) and Rowe et al. (2014a,b) experiments (modified from Rowe et al., 2014a,b).

The flow rate used by Ashe et al. (2014) was somewhat arbitrary. The amount of water in the airspace available to cause erosion is dependent on several factors: (i) the solar driven thermal cycle acting at the GMB/GCL interface, (ii) the resulting moisture cycle experienced by the GCL due to the solar driven thermal cycle, (iii) the initial soil moisture content of the GCL and subgrade, and (iv) the water retention curves of the GCL and the subgrade soil. All of these factors will impact the wet/dry cycle of the GCL and the amount of water available to flow down-slope. The initial tests (Ashe et al., 2014) were conducted on GCL2 with the white nonwoven facing up and were intended simply to identify whether erosion could occur under these conditions. These experiments showed that erosion similar to that observed in the field could be reproduced. The first erosion hole was typically observed after only 5 to 6 cycles and in some cases after as few as 3 cycles and extreme erosion features with complete loss of bentonite were observed within about 6–8 cycles (Figs. 10 and 11).

With this confirmation that down-slope erosion could be simulated in the laboratory in an accelerated time frame, the test method was then used to study the effect of different variables such as an initial wet/dry cycle, water chemistry, flow rate, slope, prior cation exchange, and the effect of no-drying phase in the test cycle (Rowe et al., 2014a,b), and finally to assess the relative susceptibility of different GCLs to down-slope erosion (Ashe et al., 2015) as summarized below.

3.3. Factors affecting down-slope erosion

This section examines the effects of a number of factors on down-slope erosion of bentonite from GCL2 as described in detail by Rowe et al. (2014b). Except where otherwise noted, all specimens were subjected to an initial wet/dry cycle prior to the tests and were inclined at a slope of 3H:1V.

3.3.1. Effect of initial wet–dry cycle

Rowe et al. (2014b) examined the potential for down-slope bentonite erosion if "rainwater" were to run down a newly placed GCL2 before it had been exposed to any wet/dry cycles. They reported that, irrespective of whether it was deionized water or tap water (39 ppm calcium) running at 0.9 L/h over the surface of the cover geotextile and down the GCL, it was not significantly absorbed and no erosion was observed with 17 and 27 cycles. Thus it is considered unlikely that a flow of rainwater down this GCL would cause down-slope bentonite erosion in the absence of the GCL having first hydrated and then dried.

In contrast, when specimens of the same GCL2 were first allowed to hydrate to 100% moisture and then dry, a similar imposed 0.9 L/h surficial flow of water was absorbed into the bentonite within 1–2 cycles and early erosion features were typically observed within 5–6 cycles with deionized water dripping on the surface where one wet/dry cycle was comprised of an 8 h wetting phase (i.e., when the flow valve open allowing water to flow over the GCL) followed by a the 16 h air-drying phase at room temperature (≈20 °C), totalling 24 h. This demonstrated that an initial wet/dry cycle was essential for the development of down-slope erosion in these experiments. This was probably because the drying of the hydrated bentonite caused desiccation cracks. These cracks provided a path for, and channeling of water flow in the GCL structure which loosened bentonite particles and carried them away. A second potential factor was swelling of the bentonite into the geotextile eliminated the hydrophobicity of the cover geotextile.

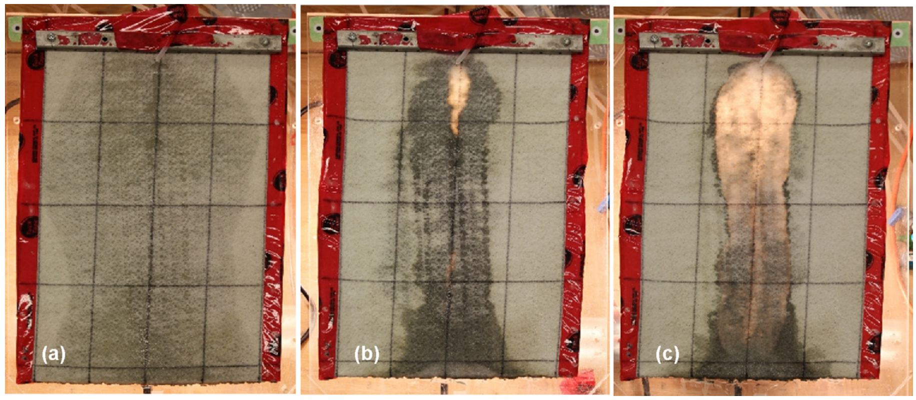

Fig. 10. Laboratory specimen of GCL2 photographed on inclined light table and photographed after: (a) Cycle 2, (b) development of first erosion hole, 'E', at Cycle 5, and (c) development of irrecoverable erosion, 'EE', at Cycle 11.

Fig. 11. GCL2 Cross section showing zones of eroded bentonite over a width of 50 mm (center of photo). Photograph looking 'up slope' at test termination.

3.3.2. *Effect of water chemistry*

There is reason to suspect (Moreno et al., 2011) that when in contact with water of very low ionic strength, the repulsive forces between clay particles would make the bentonite particles more prone to being suspended and carried away with the flowing water than if the water had higher ionic strength. Indeed, as already discussed above, the flow of deionized water caused the development of an erosion hole ('e' or 'E' features) in typically 5–6 cycles (e.g., Fig. 10b). Once an erosion feature developed it rapidly grew to irrecoverable erosion ('EE'; with little or no bentonite over a width > 25 mm) after about 6–8 cycles and which extended from the top to bottom of the specimen after about 9–10 cycles (Fig. 10c shows an example after 11 cycles).

Deionized water can readily arise in the field from the "solar still" effect of moisture evaporating from a GCL into the airspace below a geomembrane and the subsequent condensation of that water vapour when the exposed geomembrane cools at night. Composite liners are not generally used to retain deionised water (a notable exception being a composite liner for a pond containing water purified by reverse osmosis in some leachate treatment and shale/coal gas extraction processes, in which case down-slope erosion is an issue to be considered). Most fluids to be contained can be expected to have some ionic strength. The question then arises as to what effect leakage of this fluid through a small hole in the geomembrane (e.g., on a side slope of a lagoon) might have on the potential for down-slope bentonite erosion from a GCL beneath a wrinkle in an exposed geomembrane. Rowe et al. (2014b) reported results from experiments conducted using Kingston tap water (39 ppm of calcium), a simulated groundwater (232 ppm of calcium) and simulated landfill leachate (1024 ppm of calcium). It was assumed here that the geomembrane was exposed and the hole is just below the high water level but that the water level goes up and down so that the geomembrane still gets heating cycles from the sun and the hole is periodically submerged providing a hydration cycle.

Experiments were conducted using Kingston tap water at flow rates ranging from 0.003 L/h to 3 L/h however no erosion holes were observed up to 360 cycles that the tests were run. Although some widening of desiccation cracks was observed when the specimens were in a dry state, these cracks healed upon rehydration.

Specimens tested with the QUELTS pore water calcium concentration (232 ppm) and simulated landfill leachate for 45 cycles did not produce any erosion features. Thus, it would appear that there is a low probability of down-slope bentonite erosion due to water with any significant ionic strength (e.g., calcium $\geq$ 40 ppm) in a case of leakage through small hole in the geomembrane in a lagoon or landfill. The potential for down-slope bentonite erosion appears to be restricted to situations where a GCL is part of an uncovered composite liner (or possibly a pond for reverse osmosis water as noted earlier).

3.3.3. *Effect of flow rate*

The forgoing has established that down-slope erosion can result from deionised water dripping onto GCL2 for about 5–6 cycles, however the question remains as to the effect of flow rate. To examine this question, experiments were conducted at flow rates between 0.2 and 3 L/h (Rowe et al., 2014b). With the nonwoven up, an early erosion or erosion feature was observed within 5–6 cycles at all flow rates. After 7 cycles, erosion 'E' (15 mm < eroded width $\leq$ 25 mm) was observed at all flow rates, although at flow rates of 2 and 3 L/h the feature at this time was classified as irrecoverable erosion 'EE' (eroded width > 25 mm). Irrecoverable erosion 'EE' was reached after 14 cycles at the lowest flow rate of 0.2 L/h. The time to the first erosion hole and, except at the lowest flow rate, the first irrecoverable erosion 'EE' feature was mostly influenced by the number of cycles and appeared to be largely independent of the cumulative flow.

3.3.4. *Effect of slope*

In addition to the side slope at QUELTS of 3H:1V (18°) discussed above, the potential for down-slope erosion on the base slope of 33H:1V (3% or about 2°) was examined for specimens of GCL2 subjected to an initial wet/dry cycle and then subjected to a flow rate of 3 L/h during the hydrating phase. Rowe et al. (2014b) reported that the slope had no significant effect on whether or not erosion occurred (consistent with the field observation at QUELTS, Take et al., 2015a), with the first erosion hole forming in 5–6 cycles in both cases. But, like in the field, there were also differences. On the flatter base slope, very minor local changes in slope, due to subtle changes in GCL thickness resulting from very minor manufacturing variability in the laboratory and also from local foundation variability in the field, caused some pooling of water on the GCL on the 3% (base) slope and a more meandering flow path on

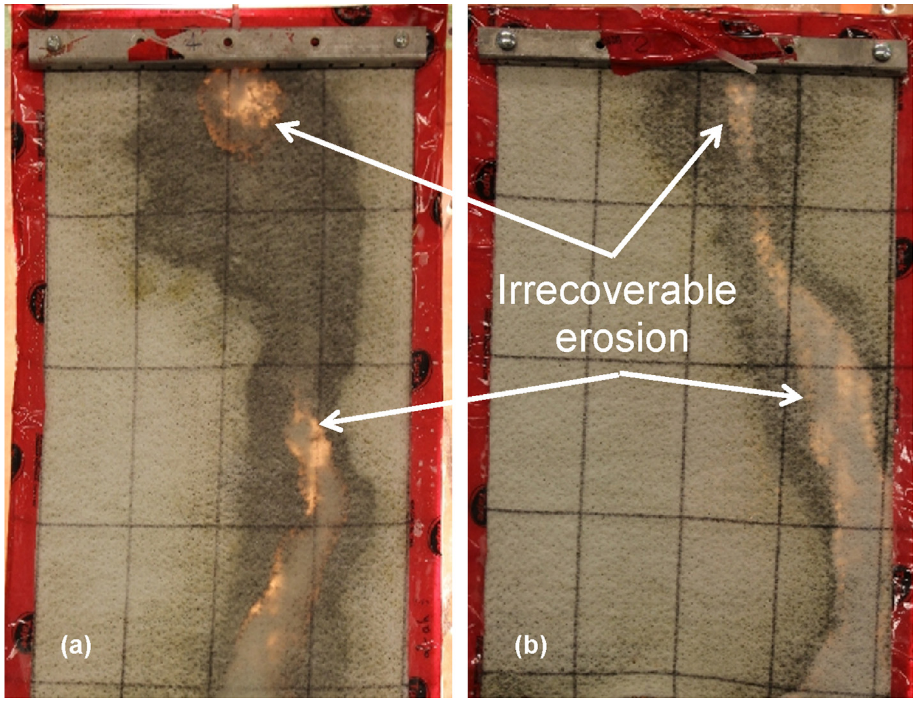

Fig. 12. Photographs of the hydration part of a cycle showing irrecoverable erosion features developed on slopes of: (a) 3H:1V (after Cycle 9), and (b) 33H:1V (after Cycle 15).

the 3% slope than on the 3H:1V slope. The progression from a first hole to significant irrecoverable erosion was slower on the base slope specimens due to a less concentrated and more variable flow path (again consistent with observations at QUELTS). For example, Fig. 12 shows irrecoverable erosion that has developed at Cycle 9 on the 3:1 slope and Cycle 15 on the 33H:1V slope.

3.3.5. Effect of cation exchange

All laboratory experiments discussed in other subsections above and below were conducted on off-the-roll samples that had not experienced cation exchange. To assess the possible effect that cation exchange may have on down-slope erosion, several experiments were also conducted (3 L/h on a 3H:1V slope) using GCL2 specimens exhumed from QUELTS I that had been subjected to 6 years of field hydration, thermal and wet/dry cycles, and cation exchange with the foundation soil (i.e., with a swell index of 14–17 ml/2 g compared to $\geq$ 24 ml/2 g for off-roll specimens). Early erosion holes were observed in 4–8 cycles for the exhumed specimens compared to 5–6 cycles for off-roll specimens. The greater variability for the exhumed specimens was most likely due to differences in the macrostructure of the specimens after six years of field exposure. The number of cycles to the development of the first erosion hole did not correlate with differences in the swell index. There was no evidence in these experiments of an effect of cation exchange on the time to develop the first erosion hole, although the number of experiments was limited and more research into the effect of cation exchange is warranted.

3.3.6. Effect of hydration and drying cycle adopted

Except for one, all experiments involved 8 h with dripping water and 16 h of air-drying. One experiment was performed on a GCL2 specimen that had been subjected to one wet/dry cycle, placed on a 3H:1V slope, and subjected to continuous dripping of deionized water at 1 L/h until a cumulative flow of 264 L; there was no drying period. The first early erosion hole developed after 9 days compared to 5–6 days (cycles) for the normal test with a 16-h drying phase in 24-h each cycle. An irrecoverable erosion feature (EE) developed after 12 days which was greater than at this flow rate with a 16-h drying phase. The faster erosion with a drying phase is likely because of the appearance of desiccation cracks during each drying cycle making the dried bentonite more susceptible to erosion when water flows again at the start of the next hydrating cycle.

3.3.7. Effect of mass per unit area (M_A)

There can be significant variability of mass per unit area (M_A) between different GCLs and even for a single roll of the same GCL (Table 2). Thus the question arises as to whether this would affect the initiation of down-slope erosion. Rowe et al. (2014a,b) reported results of erosion testing of four GCL2 specimens with M_A between 4052 and 4696 g/m^2 on a 3H:1V slope with a flow rate of 3 L/h after the specimens had experienced one initial wet/dry cycle [i.e., the slope, flow rate, and wet–dry cycle variables being equal]. The specimens all produced erosion features at 5 cycles and so there was no significant difference in performance identified in this test due to the 644 g/m^2 difference in the mass of bentonite per unit area (geotextile component was the same), however that may have been because the effect was small enough to be masked by the high flow rate.

Rowe et al. (2014a,b) reported erosion testing of two GCL2 specimens with M_A of 3553 and 4611 g/m^2 on 3H:1V slope with a flow rate of 1 L/h after specimens had experienced one initial wet/dry cycle. The specimens produced erosion features at 5 and 6 cycles, respectively. In this case the specimen with the 1000 g/m^2 lower mass of bentonite per unit area did erode earlier. Thus there is some evidence to suggest that the number of cycles to initiate the bentonite erosion is a function of the initial mass of bentonite per unit area. However, at present, there is not sufficient laboratory data to confirm this hypothesis. Also these tests report the average M_A of the specimen. There may be variability within the specimen that is also significant but the effect of this variability is much more difficult to assess. While it is a relatively simple matter to test specimens with different specimen M_A, it is much more problematic to assess the M_A at the location of the dripping point prior to testing. Indeed, the question arises as to how much local variation is required to affect the down-slope erosion. This question requires more investigation to be resolved.

3.4. Potential down-slope erosion of different GCLs in the laboratory

Ashe et al. (2015) used the technique developed by Ashe et al. (2014) to examine the potential for down-slope erosion of ten GCL products (Table 2) on a 3H:1V slope at a flow rate of 3 L/hr. The first four products (GCL1-GCL4) were the same GCLs used at QUELTS I, all of which experienced erosion in the field as previously discussed.

As at QUELTS I, it was more difficult to visually identify the development of the erosion features in GCL1 with the off-white woven geotextile up than for GCL2 with the white nonwoven up. This was, in large part, because once the first erosion hole developed, water flowed preferentially through the hole to the underlying nonwoven geotextile and then eroded bentonite from below. Once there had been essentially total erosion from an area, it could be seen with the backlight. However, without the backlight there was no obvious evidence of erosion. If the GCL specimen was turned-over, there were dark areas due to bentonite particles trapped in the nonwoven geotextile at the location of the eroded zones observed with the backlight. Despite this difficulty, there was no question that erosion occurred and in 3–6 cycles.

When GCL3 was tested with the black woven carrier geotextile up, the behaviour was similar to that for GCL1 with water flowing through the first hole and then preferentially through the nonwoven geotextile making the visual detection of the growth of the erosion features difficult. However, the black colour made the observation of erosion not only difficult in the field (as noted earlier) but also with a halogen backlight due to the absorption of light rays by the black geotextile. For both GCL3 and GCL4 with the black geotextiles facing up, erosion features that had formed were difficult, if not impossible, to detect visually with no back light. Even in normal daylight and a halogen backlight the erosion feature would not be noticed without very close inspection (Fig. 13a). From the distance at which the photo is taken (1 m above the GCL), all that is evident is the darker wet area where water had flowed over the past 8 h in this hydration cycle. The presence of irrecoverable erosion within the boxed area (width of box is 200 mm) is not apparent despite the halogen backlight which clearly showed erosion features of GCL2 or even GCL3 when the white nonwoven was placed up. When the boxed area in Fig. 13a is viewed much closer-up (0.3 m above the GCL; Fig. 13b) with the halogen backlight in normal daylight, light can be faintly seen in the eroded zone. Only when viewed in a dark room was the irrecoverable erosion feature clearly visible with the halogen backlight (Fig. 13c).

Notwithstanding the difficulty discussed above, it was found that all the GCLs used at QUELTS I (Table 1) experienced down-slope bentonite erosion in the field and in the laboratory. In the laboratory experiments, the time to first hole ranged from 2 to 6 cycles for all GCLs 1–4 with the lowest number of cycles (2 and 3) being for GCLs where a woven was up. Given that all the GCLs tested at QUELTS I were prone to down-slope bentonite erosion, this begs the question as to whether there were GCLs that would be less prone to this mechanism if a composite liner must be left exposed. This prompted Ashe et al. (2015) to conduct experiments with GCL5-GCL10 (Table 4) and the key findings are summarized below.

GCL1, GCL3 and GCL6 all had a woven carrier geotextile and a nonwoven cover geotextile (although GCL6 had heavier cover and carrier geotextiles) but differed in bentonite granularity (Table 4). All experienced down-slope erosion in the laboratory experiments, although when placed with the woven carrier up it took 5 cycles for the first erosion hole to occur for GCL6 compared to as few as 2–3 cycles for GCL3 and GCL1. There was no real difference in the number of cycles (4–5) when the nonwoven was facing up. For GCL2 and GCL5 having a scrim-reinforced nonwoven there was development of an erosion hole within 3–6 cycles. Thus, the granularity of the bentonite did not appear to significantly affect the development of down-slope erosion in these experiments. However, prior to the erosion test, in these experiments the specimens were initially hydrated to 100% gravimetric moisture content which allowed the bentonite to hydrate and swell sufficiently to form a gel with the initial particle structure being essentially lost. When they were then oven dried, desiccation cracks developed and these controlled the down-slope bentonite erosion. These tests did not examine the effect of hydration to lesser moisture contents which would allow some retained granular bentonite structure, or the effect of powdered, fine granular, and coarse granular bentonite on the uptake and loss of moisture in the hydration and drying. This may be important in the field and requires further investigation since GCL5 and GCL6 performed much better in the field at QUELTS II (see Section 4) than would be expected based on these laboratory experiments.

GCL10 (Table 4) had a similar structure to GCL2 but was much more heavily needle-punched to increase its shear strength for steep slopes. However, despite the extra needling, erosion holes were developed in a similar number of cycles for both GCL10 and GCL2, suggesting that increased needle-punching did not affect the development of down-slope erosion.

GCL7 and GCL9 both had a polyacrylamide polymer enhanced bentonite. This enhancement of the bentonite had a very beneficial effect in protecting against down-slope bentonite erosion. When GCL7 was tested with either side up or GCL9 was tested with the nonwoven cover up, no erosion hole developed after 60 cycles. Some erosion of bentonite was evident from widening of desiccation cracks that became apparent at Cycle 45 for GCL7 and Cycle 38 for GCL9, but these cracks self-healed on rehydration up to the end of testing after 60 cycles. The possible eventual development of an erosion hole cannot be excluded; however, this polyacrylamide polymer enhanced bentonite had substantially enhanced resistance to down-slope erosion and no hole formed in 10 times the number of cycles at which an erosion hole formed without this treatment under otherwise similar conditions.

Fig. 13. GCL3 with black woven-up and irrecoverable erosion 'EE': (a) photographed with a halogen backlight in normal daylight, (b) close-up of 200 mm wide area inside box shown in Figure 13a photographed with halogen backlight in normal daylight, and (c) close-up of the same area as Figure 13b with the same halogen backlight but photographed in a dark room. The black areas in Figure 13c are where there is still a significant thickness of bentonite. Modified from Ashe et al. (2015).

Table 4
Needle-punched GCLs examined by Ashe et al. (2015) (All with nonwoven cover geotextile).

Product	Used at QUELTS	Carrier geotextile[a]	Bentonite granularity	Thermally treated	M_A (g/m^2)
GCL1	I	W	fine	yes	4992
GCL2	I & II	SRNW	fine	yes	4195
GCL3	I	W	coarse	no	5808
GCL4	I	NW	coarse	no	4969
GCL5	II	SRNW	powder	yes	5881
GCL6	II	W	powder	yes	5247
GCL7	II	SRNW	fine, polymer enhanced	yes	4949
GCL8	II	W,P	fine	Polymer coated	5009
GCL9	–	W,P	fine, polymer enhanced	Polymer coated	5262
GCL10	–	SRNW[b]	fine	yes	4577

M_A = Average dry mass per unit area of samples tested in laboratory experiments.
[a] NW = nonwoven, W = woven, SRNW = scrim-reinforced nonwoven, P = polypropylene coated.
[b] This GCL was similar to GCL2 except for much heavier needle punching.

GCL8 and GCL9 had a woven carrier geotextile with a polypropylene coating and a nonwoven cover geotextile. When tested with the polypropylene coating facing up, no water penetrated through the coated geotextile, therefore no hydration or erosion features developed in the 60 cycles tested. In addition to preventing the penetration of moisture as examined here, it may also be anticipated that placing the polypropylene coating up would also prevent any significant evaporation of water into the airspace between the GCL and geomembrane hence effectively cutting off the source of water vapour that can condense and create rivulets on the GCL. Although not examined, it may be hypothesised that placing the polymer coating down would have the same net effect by preventing the GCL from hydrating from the subsoil (similar to placing a GCL encapsulated between two geomembranes) and hence also cutting off the source of water vapour. However, this approach leaves the GCL to hydrate from whatever fluid leaks through a hole in the upper geomembranes and this may have a negative effect on GCL hydraulic conductivity (Rowe, 1998; Rowe et al., 2004).

4. QUELTS II

4.1. Conditions examined

QUELTS II (Figs. 14–16) was constructed in May 2012 to allow an evaluation of (a) the development of down-slope erosion features with time from first construction, (b) the effectiveness of placing 0.3 m of cover soil over the geomembrane (Section [1], Figs. 14–16), (c) the effect of using a white (Section [2]) rather than black (Section [3]) geomembrane under otherwise as similar conditions as possible, and (d) the performance of four GCLs examined by Ashe et al. (2015) relative to GCL2 which was used as a control (Section [3]). Of the four new GCLs examined (GCLs 5–8; Tables 2–4), two had powdered bentonite (GCL5 in Section [4] and GCL6 in Section [6]) to establish whether their performance was similar in the field to that in the laboratory tests discussed earlier. One GCL (GCL7, Section [5]) had polyacrylamide polymer enhanced bentonite but was otherwise similar to GCL2. Finally, GCL8 (Section [7]) had a polypropylene coating placed facing up but was otherwise similar to GCL1 used in QUELTS I with the woven up. As noted earlier all four GCLs used as QUELTS I (GCLs1-4; Tables 1–4) experienced significant down-slope bentonite erosion; GCL2 below a black geomembrane was selected as the control case simply because it was easier to visually identify down-slope erosion if it occurred again at QUELTS II.

Based on dry sieve analyses, the subgrade material from QUELTS has been classified as silty sand (Brachman et al., 2007; Rayhani et al., 2011) with 35% non-plastic fines passing the No. 200 sieve (0.075 mm). The study for QUELTS II examined the effects of dry sieving versus wet sieving on the classification of the soil and also the spatial variability of the soil across the lined region of QUELTS II.

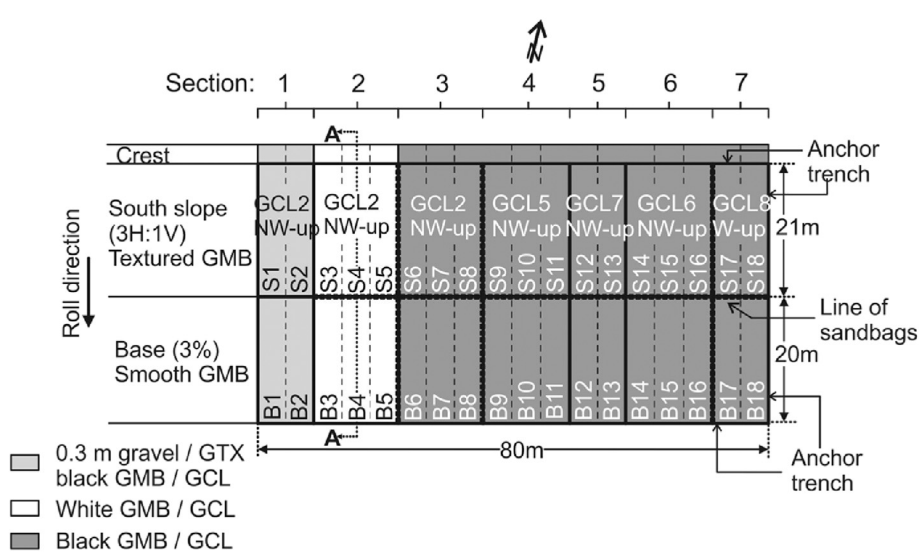

Fig. 14. Plan view of QUELTS II.

Fig. 15. QUELTS II during construction in May 2012. Textured 1.5 mm HDPE geomembrane was placed on the slope and a smooth geomembrane on the base. Sections from west to east (left to right): [1] GCL2 with 0.3 m gravel, [2] GCL2 with white GMB, [3] GCL2 (control; as per Section 3 of QUELTS I), [4] GCL5, [5] GCL7, [6] GCL6, and [7] GCL8 with polypropylene coating-up (Table 1).

Fig. 16. Western three sections of QUELTS II viewed looking north. From west to east (left to right): [1] GCL2 covered by black geomembrane, geotextile protection layer, and 0.3 m gravel, [2] GCL2 covered by a white geomembrane, and [3] GCL2 covered by a black geomembrane.

Gravimetric water content and both dry and wet sieve analyses were performed on surficial soil samples extracted along the centre-line of each GCL panel immediately before each GCL panel was installed during construction. Table 5 summarizes the GCL panel number, test section, location relative to the crest of the slope (distances exceeding 20 m are located on the base portion of the site), the gravimetric water content, and the percent fines based on both the wet and dry sieve analyses at a number of these locations. Fig. 17 shows a contour map of the gravimetric water content across the full site obtained for the surficial soil samples. The soil was non-plastic with negligible clay. The wet sieve silt content (passing the No. 200 sieve) was consistently higher than the dry sieve silt content. The wet sieve silt content ranged from 33% to 80% while the dry sieve silt content ranged from 31% to 57%. The largest difference between the wet and dry sieve silt content was 31% observed for a sample with an initial water content of 15%–16%. Generally, the higher the initial water content the higher the percent silt content as might be expected since the silty fines have a higher capacity for water retention. Some exceptions were observed, viz: (i) samples near the south anchor trench on Panels 7–18 had higher water contents (10%–14%) with lower silt contents (45%–58%, wet sieve) likely due to the slight (3%) slope on the base directing moisture to this area; and (ii) samples from GCL Panel 18 generally had higher initial water contents with lower silt contents,

Table 5
Variability of soil moisture content and grain size distribution obtained for surficial soil samples collected prior to the installation of each GCL panel.

	Panel#	Distance from top of slope (m)	Gravimetric water content[a] (%)	Percent passing No. 200 sieve, wet sieve (%)[b]	Percent passing No. 200 sieve, dry sieve (%)[c]
0.3 m gravel/GTX/black	1	10	13	71[g]	53[f]
GMB: GCL2	2	32	13	73[g]	51[f]
White GMB[d]: GCL 2	4	0, 10, 20,28	11, 12, 15, 11	69[f], 69[f], 80[g], 68[f]	48[e], 48[e], 49[e],46[e]
Black GMB: GCL 2	6	0, 10, 20, 30	13, 10, 16, 9	79[g], 71[g], 76[g], 67[f]	-, -, -, -
	7	20, 36	15, 11	73[g], 57[f]	43[e], 57[f]
	8	0, 10, 20, 36	15, 11, 9, 13	74[g], 70[g], 65[f], 50[f]	47[e], 40[e], 46[e], 43[e]
Black GMB: GCL 5	9	20, 36	7, 8	64[f], 59[f]	48[e], 42[e]
Black GMB: GCL 7	13	8, 36	9, 13	43[e], 50[f]	36[e], 40[e]
Black GMB: GCL 6	14	8, 18, 26, 36	7, 5, 7, 13	34[e], 33[e], 47[e], 54[f]	31[e], -, 41[e], 39[e]
	16	18, 26, 36	7, 10, 14	41[e], 45[e], 58[f]	36[e], 34[e], 40[e]
Black GMB: GCL 8	18	0, 38	14, 12	44[e], 53[f]	-, 53[f]

[a] Following ASTM 4643-08.
[b] Following ASTM D2217-98 (withdrawn 2007).
[c] Following ASTM D422-63.
[d] GMB = geomembrane.
[e] Silty sand (SM).
[f] Sandy silt.
[g] Silt with sand.

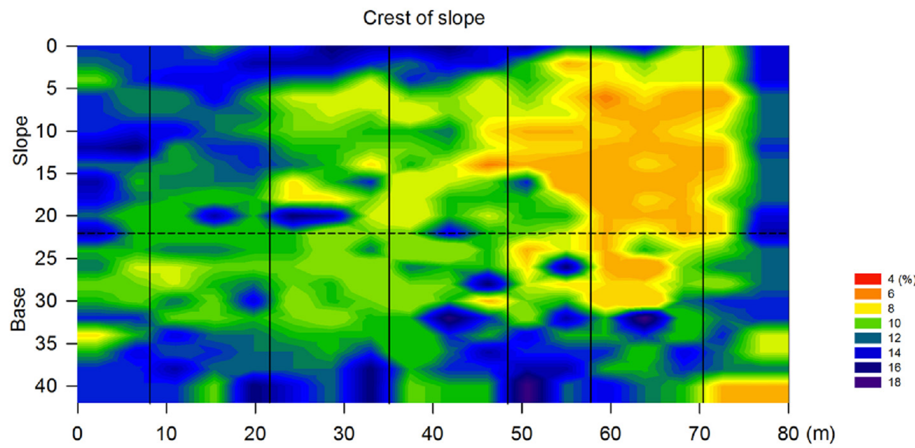

Fig. 17. Contour map of soil gravimetric water content (%) just prior to liner installation at QUELTS II (distances in m measured from top of slope (north) and east edge of base).

since this portion of the site was unlined for QUELTS I and added to the lined portion of QUELTS II, exposing the soil to precipitation prior to covering with liner material.

Some spatial variability of the soil was observed across the site. The western half of the site (GCL Panels 1–7), was generally siltier with higher initial water contents than the eastern half of the site (GCL Panels 8–18) which was generally sandier with lower initial water contents. Local variability was also observed where two soil samples on Panel 11, 2 m apart, had very different initial water contents (16% and 7%) and wet sieve silt contents (74% and 34%). The initial water content and the grain size of the soil can be expected to impact the hydration of the overlying GCL and, at least in part, helps explain variable hydration of a given GCL.

Wet sieving allows breakup of any sand sized silt clods in the soil resulting in higher silt content than when dry sieved where these same dry clods would be retained on the #200 sieve. Since the subgrade is not fully saturated, the wet sieve analysis likely overestimates the silt content that would influence moisture uptake from the subgrade and in reality the natural subgrade likely behaves as a material with silt content between the wet sieve upper bound and the dry sieve lower bound. All but four of the dry sieve analyses classify the soil as silty sand which is consistent with Rayhani et al. (2011) and Brachman et al. (2007). With the wet sieve method, the soil is classified as either silty sand, sandy silt or silt with sand. The western half of the site (GCL Panels 1–9) is sandy silt and silt with sand while the eastern half of the site (GCL Panels 13–18) is sandy silt and silty sand.

The variability in the silt content could affect the water retention characteristics of the subgrade. The variable initial subgrade moisture content would likely have some effect on the time to initial hydration of the overlying GCL. It is expected that the higher moisture in the western half of the site would allow Sections 1–3 to hydrate a little faster than Sections 4–7 and also increase the moisture content of the GCL. A moister subgrade could result in a moister GCL and in turn provide more moisture available for evaporation into the GMB/GCL airspace (other things being equal), thus decreasing the time to initial hydration and increasing the amount of water available for erosion to occur. Although the time to initial hydration must be considered, the time to subsequent drying is just as important. For erosion to occur, the GCL must experience an initial wet/dry cycle as confirmed by Rowe et al. (2014b). If the GCL remains hydrated, desiccation cracks will not form and erosion likely will not occur. As well, other factors must also be considered: (i) the solar driven thermal cycle acting at the GMB/GCL interface, (ii) the resulting moisture cycle experienced by the GCL due to the solar driven thermal cycles, (iii) the water retention curve of the GCL, and (iv) the water retention curve of the subsoil. All of these factors will impact the rate at which the GCL will experience the initial wet/dry cycle and the amount of water available to flow down-slope. The subgrade moisture in the western half of the site could have allowed GCL2 to hydrate faster than GCLs 5–8. But during the first inspection in July, all GCLs appeared to be hydrated and no erosion was observed. Variable initial subgrade moisture contents likely resulted in different initial GCL hydration rates but ultimately it was the subsequent rate of drying that would likely impact the time for erosion to occur. Local variability (over < 2 m) of subsoil moisture content within a section would have allowed some areas of each test section to experience different hydration rates. If the initial subgrade moisture content governed the erosion rates, erosion features should have been observed for all GCL types (with the exception of GCL8) but this was not the case. While the initial moisture content of the subsoil is an important factor to consider with respect to down-slope erosion, the level of subsoil moisture variability on this site is not considered to have been a governing factor affecting the down-slope erosion of the GCL. The GCLs ability to retain moisture is considered to be of greater importance than the initial subgrade water content and was likely a more dominating factor affecting the different down-slope erosion responses.

4.2. Non-destructive inspection for erosion

For QUELTS II, a non-destructive technique was developed to allow the study of erosion features without cutting the GCL. This technique involved the use of a 300 × 300 × 8 mm thin light emitting diode (LED) light panel attached to an aluminium tray that was slid beneath the GCL panel with access from the GCL panel overlaps (Brachman et al., 2014b, Fig. 18). A frame with blue LED lights around the perimeter and a 360 × 360 mm inside dimension

Fig. 18. Thin (300 × 300 × 8 mm) LED light panel attached to tray being inserted below a panel at an overlap using push–pull rods.

Fig. 19. Camera being set-up in portable dark-room after insertion of light table to the target location. Once camera is set up, the top of the dark room was placed and the camera triggered remotely.

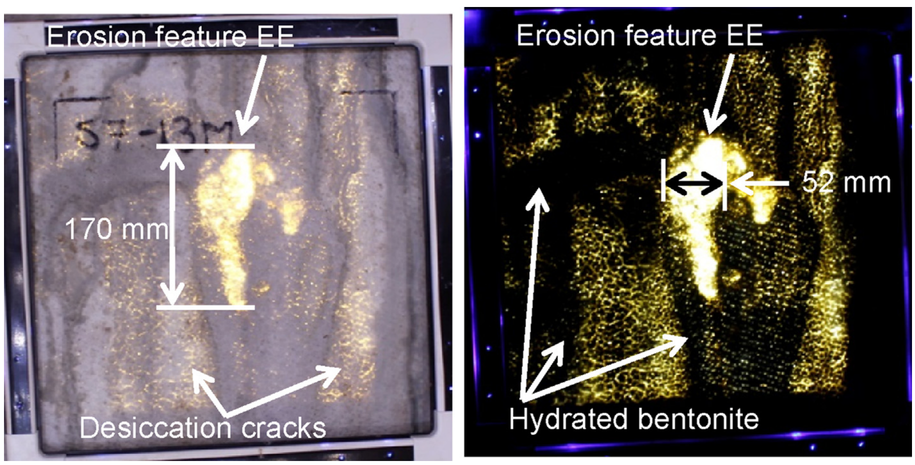

Fig. 20. Photographs taken in field dark room (Fig. 19) on 27 May 2013 (i.e., 1 year after construction of QUELTS II) at a location 13 m down the slope on Section 3 (GCL2 below black geomembrane) showing an irrecoverable erosion feature that had developed at this time. Areas with no light shining through are hydrated bentonite. Dappled areas are locations where there is bentonite and the light is shining through desiccation cracks that will self-heal on hydration.

was placed over the GCL at the location of the LED panel for scale. The bottom portion of a very light-weight (cardboard) mobile dark room was placed over the location of interest, a high resolution camera was mounted above the light panel, and the top of the dark room was put into place (Brachman et al., 2014a,b, Fig. 19). Photographs were then triggered externally.

With the LED light on, two photographs were taken: (a) one with an internal light in the dark room turned on (Fig. 20a), and (b) one with the internal light off (Fig. 20b). The photos in Fig. 20 show an irrecoverable erosion feature (EE; width > 25 mm) that is 52 mm wide at its widest and 170 mm long that has developed in the 12 months since QUELTS II was constructed. This is consistent with the observation of extreme erosion (and irrecoverable erosion) observed at QUELTS I on patches placed after 3.6 years and inspected at 4.7 years discussed earlier (Fig. 5). There is a second erosion feature developing to the right of the main feature in Fig. 20 and it appears that, with more time, they may connect. Also evident in Fig. 20 are areas of hydrated bentonite (no light in Fig. 20a and black in Fig. 20b) and areas of previously hydrated bentonite that have dried and desiccated (dappled areas). These photographs show that for a composite liner left exposed at the QUELTS site for one year, the condition of the GCL can vary substantially in a small distance from well hydrated bentonite, to dried and desiccated bentonite (capable of self-healing when rehydrated) to areas where there is no bentonite remaining over an area too large to be repaired by swelling of bentonite when the GCL re-hydrates.

QUELTS II was inspected after 1.5 months (July 2012), 3.5 months (August 2012), 6 months (November 2012), 12 months (May 2013), 15 months (August 2013), and after 28 months (September 2014) as discussed in detail by Rowe et al. (2016). Over the first 15 months of monitoring, significant erosion was observed in the control section [3] (as observed in QUELTS I) but not in some other sections. A particularly important finding was that when GCL2 was installed as recommended by the manufacturer (with a 0.3 m ballast layer placed over geomembrane within a week), there was no erosion and the GCL was in excellent condition. The use of a white geomembrane instead of the black geomembrane had beneficial effects in terms of reducing geomembrane temperature and consequent wrinkling (Rentz et al., 2016b). It also increased the time to the development of an erosion feature but, for a GCL susceptible to erosion, it did not eliminate the potential problem (Rentz et al., 2016a).

After 15 months there was negligible erosion observed for GCL7 (Section [5]) however after 28 months there were two erosion features (one irrecoverable erosion feature 'EE' and one irrecoverable extreme erosion feature 'EEE') observed on the slope.

GCL5 (Section [4]) and GCL6 (Section [6]) experienced hydration and drying and early erosion ('e') features (Fig. 21), however in some cases these early erosion features observed at a given time had self-healed at a subsequent time (Fig. 22). After 28 months in the field, nothing more than an early erosion feature was observed for GCL5 or GCL6 suggesting that there was something different between the field and laboratory behaviour of these two GCLs with

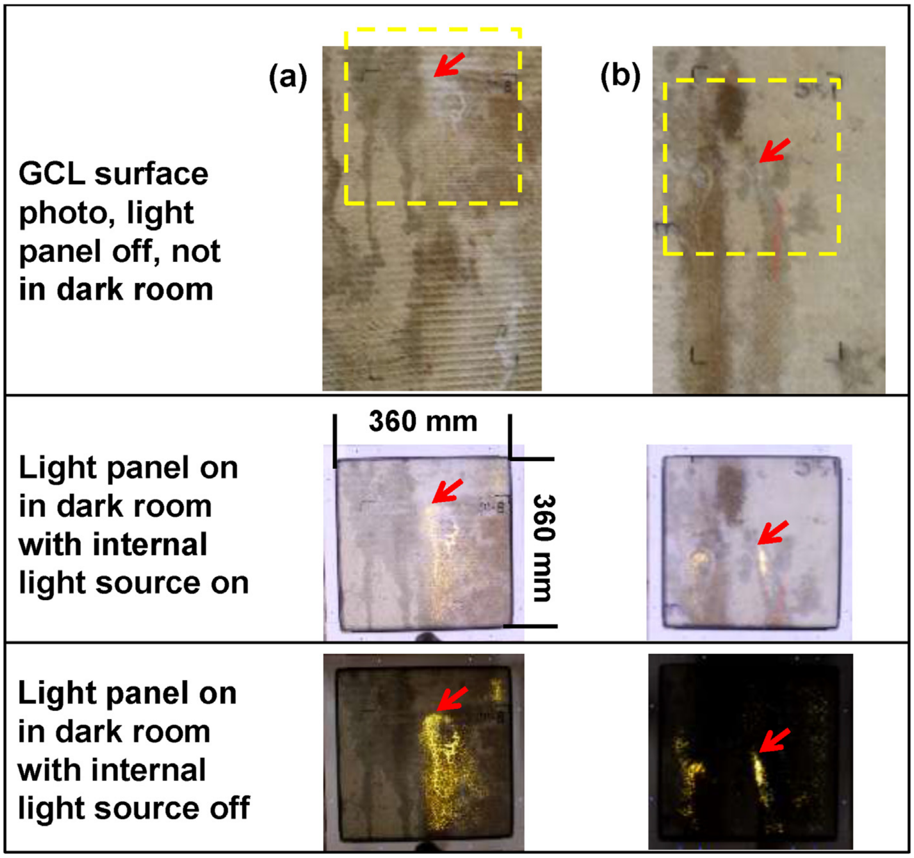

Fig. 21. Back-lit erosion photos taken after 6 months exposure (November 2012): (a) early erosion 'e' on GCL5, and (b) early erosion 'e' on GCL6. The yellow squares are 360 × 360 mm identifying the location of inner edge of the frame shown in light panel photos. The upper photo is taken in normal daylight; the middle photo is taken from inside the portable dark-room with the internal light source on; the lower photo is taken from inside the portable dark-room with the internal light source off. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

powdered bentonite that was not evident for the GCLs with granular bentonite. The explanation for this requires more investigation.

Of the GCLs examined at QUELTS II, GCL2 had the lowest average M_A and suffered the most from down-slope erosion. This begs the question as to whether the two observations are related? Based on the laboratory tests (Section 3.3.7) there is some evidence to suggest that erosion occurs faster with a lower mass of bentonite per unit area, but insufficient evidence to draw a definitive conclusion. It is thought that the lower M_A may have been one contributing factor but there are many other factors to consider including: (i) grain size of the bentonite, (ii) presence/absence of a polymer additive, (iii) mass of the geotextiles, and (iv) if there is a coating or film on the geotextile or not.

There was no erosion of GCL8 with intact polypropylene coating facing up (Section [7]) after 28 months (Fig. 23). However, the expansion and contraction of the black geomembrane caused the underlying flap at the geomembrane weld to scrape the thin coating of GCL8 (scuff marks are shown on Fig. 24a and scuffed material on the weld in Fig. 24b). Over the 28 months of exposure at QUELTS II, this scuffing did not cause sufficient loss of material to impair the positive effect of the coating in preventing down-slope erosion, however the effect of longer or more extreme thermal cycles is not known.

Based on the available laboratory and field data, if a composite liner must be left exposed then the use of a multicomponent (coated) GCL with the coating facing upward appears to offer the overall best performance from the perspectives of avoiding down-slope erosion (discussed above) and limiting shrinkage (not discussed here), although the combined use of a white geomembrane and a coated GCL would appear to be the best solution if the liner must be left exposed since the white geomembrane would reduce the magnitude of thermal cycles (Rentz et al., 2016a,b) and hence can be expected to reduce the scuffing discussed above and also the shrinkage of the GCL. However, caution is still required even with a multicomponent GCL (coating facing up). In particular, cutting of samples for geomembrane weld testing (or other tests) introduces the risk of cutting the coating on the GCL as happened at one location at QUELTS II after 15 months (Fig. 25a). Here a 70 mm cut allowed loss of bentonite around the cut (Fig. 25b and c; Fig. 26) over the next 15 months (when photographs were taken). More severe cuts could allow moisture loss and increased potential for erosion. Also an over-exuberant welder doing a patch weld melted the GCL coating (Fig. 27) which allowed the initiation of local erosion at the location of the loss of coating. While the effect here was relatively minor at the time of inspection, it may have become more significant with time. If this could happen on a research site (where the worker knew the site would be examined in detail at a later time when he was doing the weld – what happens when no one is going to do an inspection?). Thus a multicomponent (coated) GCL needs to be used with sufficient care to avoid damage during construction activities.

5. Laboratory versus field results

The bench scale laboratory tests described in Section 3 provided insights that aided in the selection of GCLs for QUELTS II. Table 6 shows a comparison of laboratory observations made by Ashe et al. (2015) for the same configurations as in the field and the

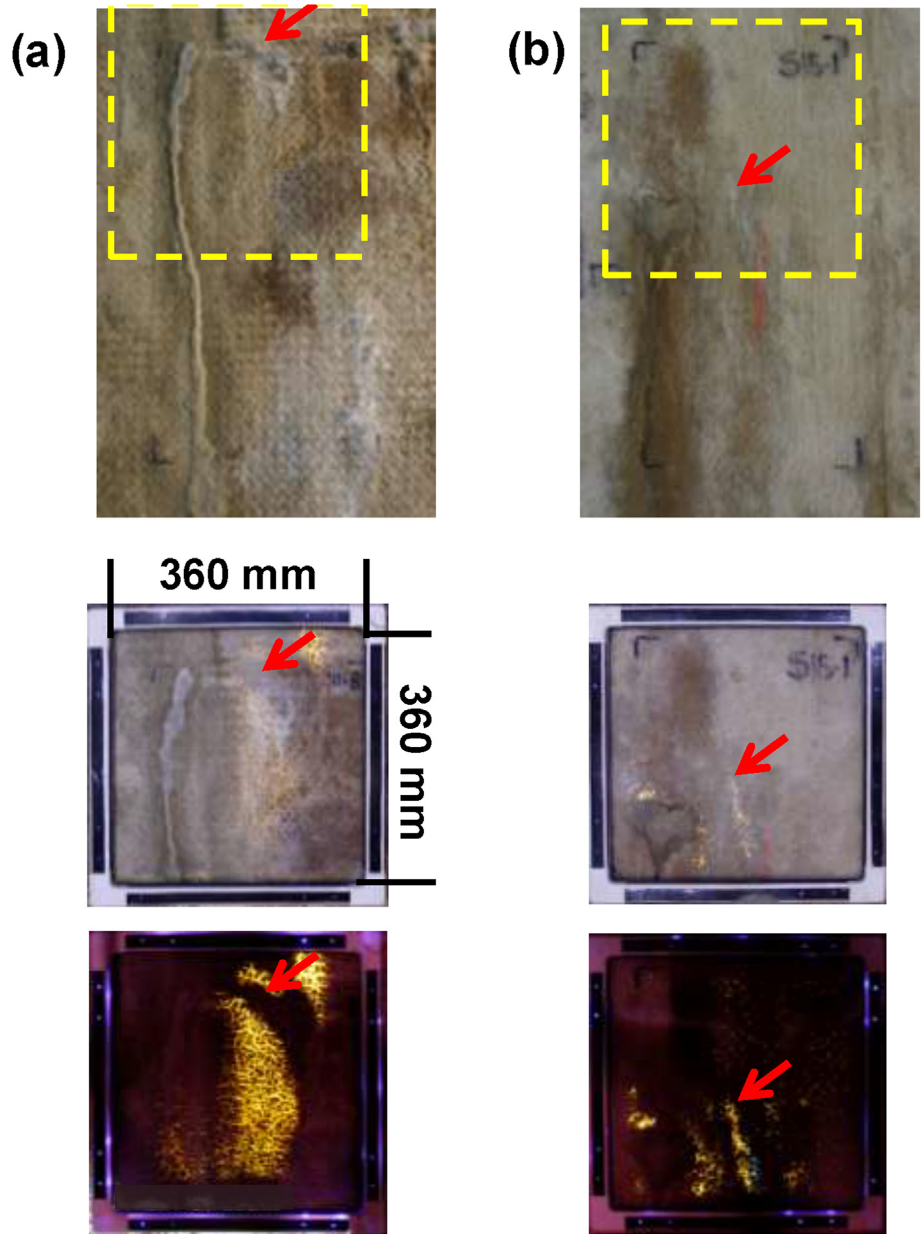

Fig. 22. Back-lit erosion photos taken after 12 months exposure (May 2013): (a) the feature indicated by the arrow on GCL5 was early erosion 'e' after 6 months exposure (Fig. 21a) and is now hydrated and healed at the time of inspection but a new early erosion 'e' feature has formed in the upper right corner of the framed area, and (b) the feature on GCL6 was early erosion 'e' after 6 months exposure (Fig. 21b) and is still an 'e' feature. The yellow squares are 360 × 360 mm identifying the location of inner edge of the frame shown in light panel photos. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

field observations discussed by Rowe et al. (2016) for GCL2, and GCL5 - GCL8. Ashe et al. (2015) observed erosion features for GCL2, GCL5 and GCL6. In the laboratory, the powdered bentonite GCL products, GCL5 and GCL6, eroded after 3 and 5 cycles while the fine grained bentonite product, GCL2, eroded after 5–6 cycles. At QUELTS II, GCL5 and GCL6 did not experience any significant erosion (i.e., nothing larger than an 'e') after 28 months' exposure while GCL2 experienced erosion after 6 months exposure. The varying erosion behaviour observed in the laboratory and field for GCL5 and GCL6 may be attributed to a combination of several factors affecting erosion: bentonite granularity, type of bentonite (mineralogy), type of geotextile, and mass per unit area of bentonite. These factors appear to have contributed to better water retention observed for these two GCLs in the field (i.e., GCL5 and GCL6 were typically moister than GCL2 during field investigations). The apparent improved water retention (inferred to imply greater resistant to drying) may have reduced the wet–dry cycles acting on them relative to GCL2 when subject to the same climatic conditions. This would explain the negligible erosion observed for GCL5 and GCL6 relative to GCL2 in the field compared to similar behaviour in the laboratory (when they were all subjected to the same, relatively high 3 L/hr, dripping cycle followed by the same drying cycle).

In the laboratory tests, GCL7 and GCL8 did not experience any erosion after 60 cycles, although GCL7 did have expanded desiccation cracks that are a precursor to the development of an erosion feature. In the field the performance of GCL7 was very consistent with the laboratory study for the first 15 months but after 28 months of exposure it had experienced erosion in the field. Although more research is needed to establish the reason, it is hypothesised that the polymer was leached out of the bentonite at

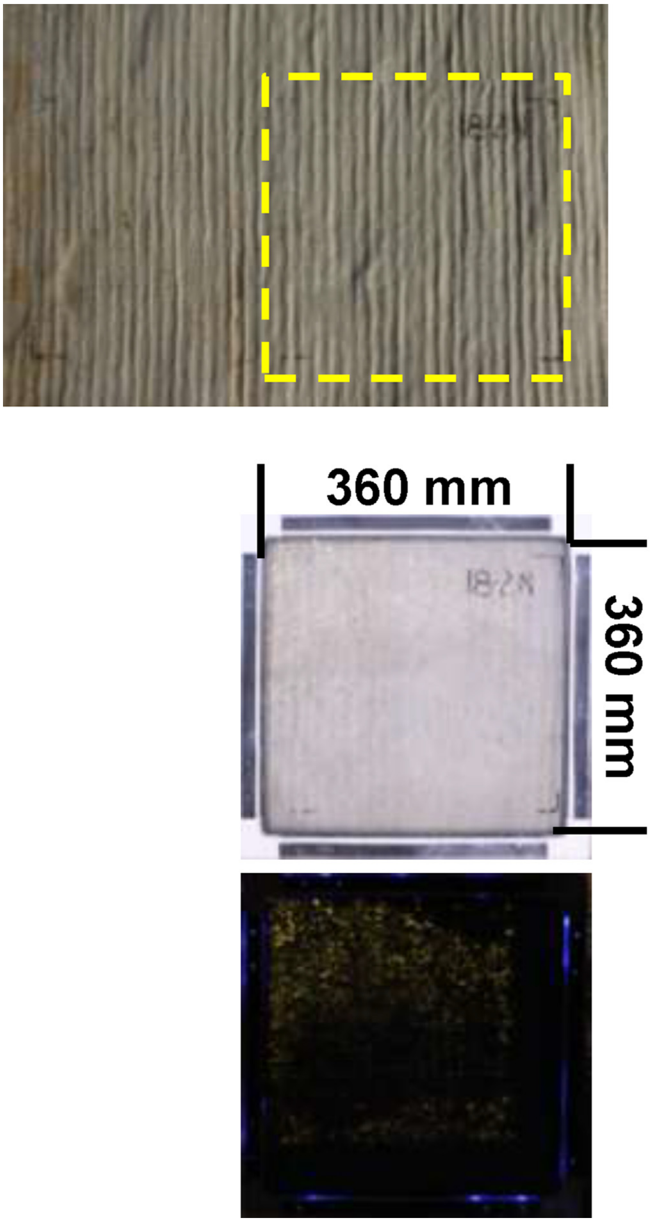

Fig. 23. No evidence of erosion on GCL8 beneath a black geomembrane after 28 months exposure (September 2014). Light panel photos show largely uniform desiccation cracking with very narrow openings that do not let significant light through; compared to the photos of other GCLs.

locations of higher flow some time between 15 and 28 months and once the polymer was removed the bentonite was free to erode. Significant erosion features only occurred at two locations with an eroded area of only approximately 0.04 m^2 in over 380 m^2 (i.e., 0.01%) of GCL7 placed in the field; nevertheless, it is a warning that bentonite additives may not last forever.

GCL8 performed better than any other GCL product in both the laboratory tests and, where the coating was not compromised, in the field. GCL8 showed no signs of erosion after 60 cycles in the laboratory experiment and no evidence of any erosion after 28 months in the field. In the laboratory, the polypropylene coating prevented the constant water source from infiltrating through the upper geotextile and washing out the bentonite. In the field, an intact coating prevented moisture from passing through the upper geotextile into the GMB/GCL interface which removed the erosion water source altogether.

6. Conclusion and practical implications

Leaving a composite liner exposed is known to lead to problems with desiccation of compacted clay liners (Rowe, 2012). It can also lead to GCL panel shrinkage (Thiel et al., 2006). This paper has summarized the findings from recent research into the mechanism of down-slope bentonite erosion which can, under certain conditions, leave significant areas of the GCL without sufficient bentonite to provide an adequate hydraulic barrier. The key conclusions and practical implications based on QUELTS I, the laboratory studies reported, and 28 months of monitoring at QUELTS II are summarized below. Careful consideration would need to be given to the similarities and difference between the site conditions at QUELTS, those in the laboratory experiments, and those at any specific site before the findings were applied to any particular design.

1. When the geomembrane is left uncovered for a period beyond that recommended by manufacturers and is heated by solar radiation, moisture evaporates from the GCL and the water vapour accumulates in gaps between the geomembrane and GCL (especially at wrinkles which form in the geomembrane). When the geomembrane cools, the water vapour condenses as distilled water on the underside of the geomembrane and then migrates in the space between the geomembrane and GCL (especially at wrinkles) until it drops down onto the GCL and then runs down the GCL. Drop-down points can arise from a number of conditions including: very minor irregularities in the foundation grade, intersection of wrinkles, and, especially, at welds in the geomembrane. Down-slope bentonite erosion arises from the cumulative effects of bentonite being transported by small quantities of condensed water vapour flowing along the interface between the geomembrane and GCL.
2. Down-slope bentonite erosion is most likely to occur at critical locations such as beneath wrinkles in the geomembrane and at geomembrane seams. In general, the loss of bentonite from the GCL is difficult to detect visually without the use of a back-light and even then difficult to detect on GCLs with black geotextiles.
3. Down-slope bentonite erosion was more extensive on a 3H:1V slope than a 33H:1V (3%) slope, however it can occur on a 3% (2°) base slope.
4. Relatively simple laboratory tests were able to reproduce the down-slope erosion observed at QUELTS I and erosion holes (loss of bentonite over a width exceeding 15 mm). The down-slope erosion was only observed for GCLs that had experienced a hydration and drying cycle. For these GCLs, the holes developed after only about 5–6 cycles of down-slope moisture movement and overnight drying. How long this would correspond to in the field would depend on the site specific conditions.
5. In the laboratory tests, erosion only occurred with down-slope flow of distilled water. The presence of even a low ion concentration (39 ppm calcium) was sufficient to prevent down-slope erosion for at least up to 365 cycles. Thus, down-slope erosion of the form discussed here does not seem likely due to leakage of other water (e.g., groundwater, leachate, normal drinking water, etc.) through a hole in the geomembrane. It may be an issue for water ponds containing water treated by reverse osmosis.
6. There was no erosion observed for the composite liner covered by 0.3 m of gravel after 28 months' exposure at QUELTS II.
7. There was no evidence of any erosion for the GCL placed with an intact polypropylene coating facing up after 28 months'

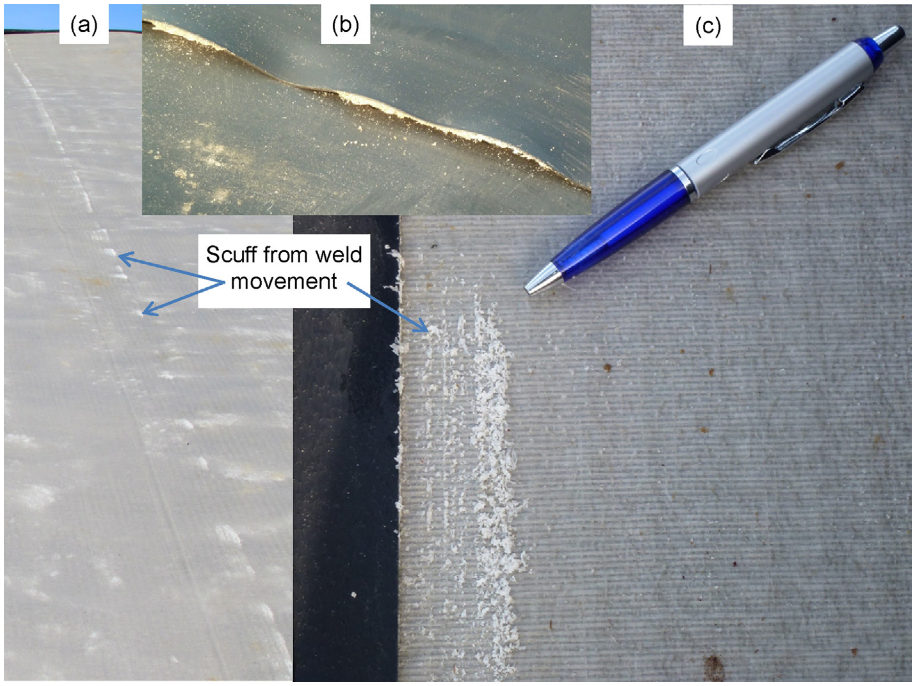

Fig. 24. Scuffing of the 100 μm polypropylene coating of GCL8 due to the movement of weld due to thermal expansion and contraction of the geomembrane: (a) scuffing of the GCL coating along almost entire weld, (b) coating material accumulated on the lower geomembrane overlap at the weld, and (c) polypropylene coating accumulated on weld overlap and scuffing of GCL.

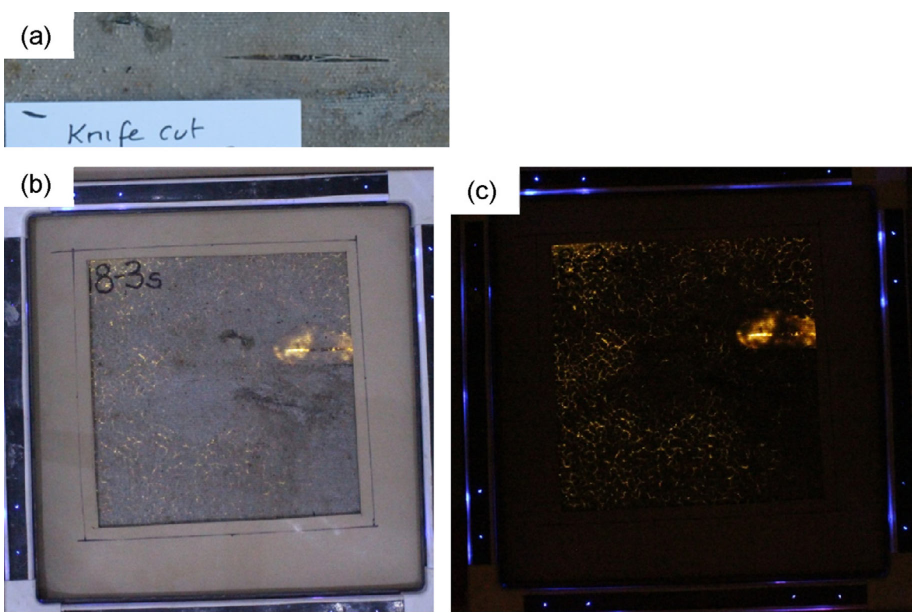

Fig. 25. Cut in coating of GCL8: (a) 70 mm knife cut, (b) darkroom photo with internal light on showing cut and bentonite loss around hole, and (c) darkroom photo with internal light off showing cut and bentonite loss around hole.

exposure. Man-made cuts in the coating (e.g., as may occur with careless cutting of weld samples for destructive testing) or burns induced by excess heat when repairing cuts in the geomembrane could create a location where down-slope erosion could occur.

8. After 28 months of exposure, the worst feature detected on either GCL5 or GCL6 was early erosion and they performed very well in the field over the period examined. There are two potential factors contributing to the reduced rate of down-slope erosion progression observed for GCL5 and GCL6 in the field relative to the GCLs used at QUELTS I: (i) a higher mass per unit area of bentonite, and (ii) the use of powdered bentonite. These GCLs appeared to retain their moisture better than GCLs 1–4 and this likely reduced the magnitude of moisture evaporation when the geomembrane was hot and hence the moisture available to drip onto the GCL when the geomembrane cooled for the specific conditions examined. However, on other sites, additional factors (e.g., initial

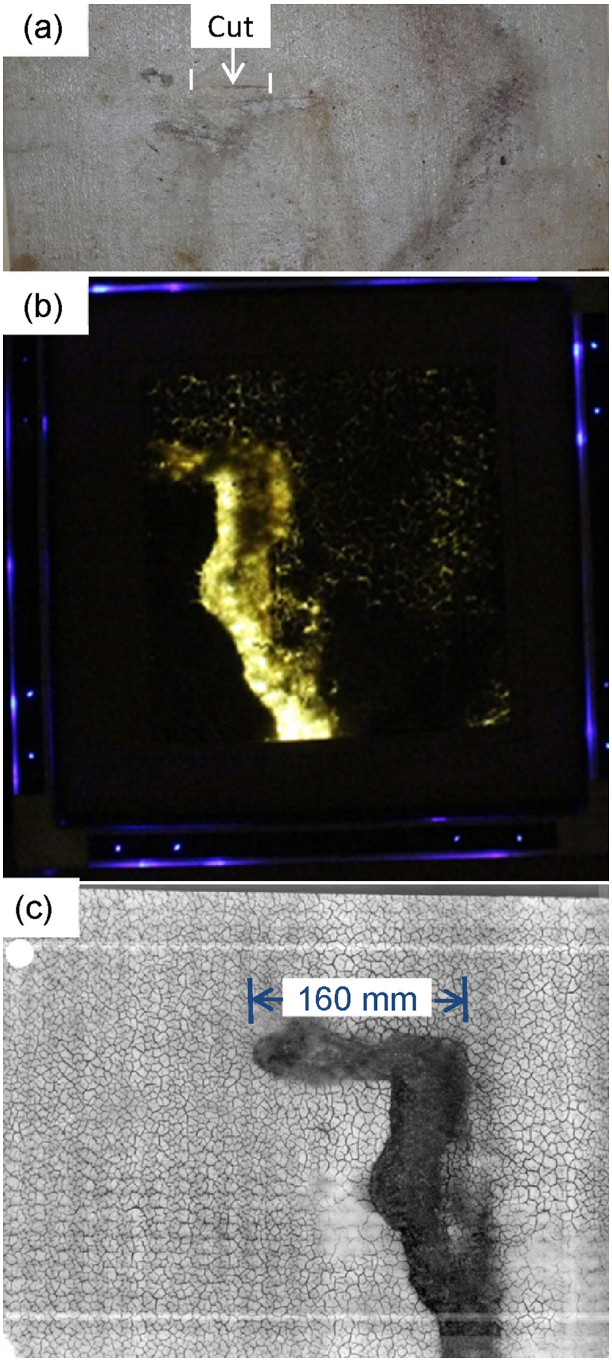

Fig. 26. Erosion feature (a) emanating from a cut in coating of GCL8, (b) darkroom photo with internal light off showing bentonite loss from below right side of hole (width of photo is 300 mm), and (c) X-ray photo showing bentonite loss at cut and below right side of hole (black area). Desiccation is visible elsewhere (short black matrix are desiccation cracks around white bentonite zones).

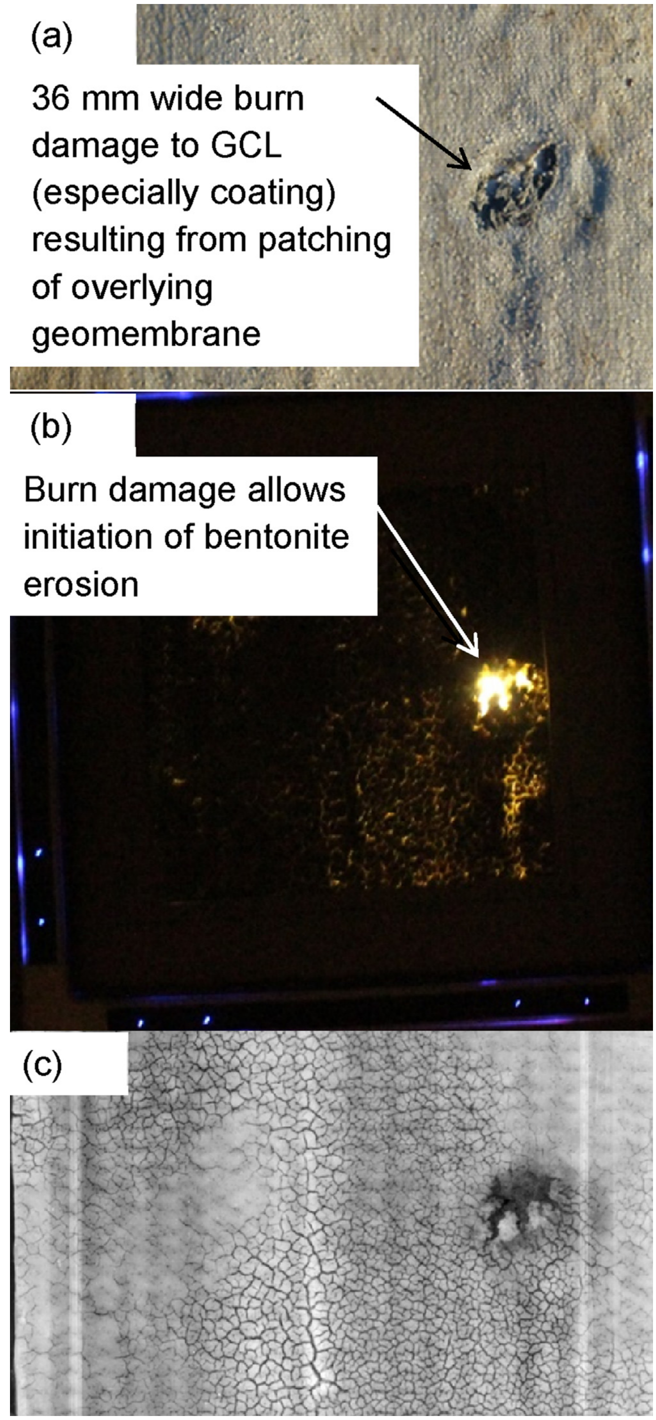

Fig. 27. Erosion feature (a) emanating from a burn in coating of GCL8 (width of photo is 300 mm), (b) Darkroom photo with internal light off showing bentonite loss from location of burn (width of photo is 300 mm), and (c) X-ray photo showing bentonite loss at burn (black area on right mid of photo).

subgrade conditions, climatic conditions) may affect the uptake and loss of water and the absence of significant erosion at QUELTS does not necessarily mean it would not occur under different conditions (as was shown in the laboratory experiments).

9. For GCLs with polyacrylamide based polymer enhanced bentonite there was some widening of desiccation cracks, indicating minor bentonite erosion, but no holes had formed in laboratory tests run up to 60 cycles or 15 months of field exposure at QUELTS II; however, after 28 months, one irrecoverable erosion feature ‘EE’ and one irrecoverable extreme erosion feature ‘EEE’ were observed on the 3:1 slope at QUELTS II.
10. Additional needle punching did not appear to prevent or reduce potential down-slope bentonite erosion.

Important practical implications from QUELTS include: (i) spot checks, as were conducted during the first 3.6 years at QUELTS I, did

Table 6
Comparison of bench scale laboratory test results and field observed erosion.

GCL	GCL configuration	Laboratory results (Ashe et al., 2015)		Field results	
		Erosion occurred?	Cycles	Erosion occurred?	Time to erosion (months)
GCL2	nonwoven up	Yes	5–6	Yes	6[a]
GCL5	nonwoven up	Yes	3	No	–[b]
GCL6	nonwoven up	Yes	5	No	–[b]
GCL7	nonwoven up	No	–[c]	Yes	28
GCL8	woven, coating up	No	–[d]	No	–[b]

[a] GCL2 beneath a black geomembrane.
[b] No erosion observed after 28 months of exposure.
[c] No erosion observed after 60 cycles but widening of desiccation cracks that are a precursor to erosion.
[d] No erosion observed after 60 cycles.

not identify a problem that had probably developed at sometime within the first year; (ii) except for GCLs with the white nonwoven up, it was generally not possible to visually identify locations where bentonite had been eroded, thus GCLs with a black or grey geotextile should not be used in composite liners unless they will be covered immediately by a soil layer (in which case the black or grey is not needed either); (iii) locations of bentonite streaks usually were not the locations of significant bentonite erosion (but rather deposition); (iv) areas of bentonite erosion can be identified by tactile inspection but this inspection likely misses many smaller eroded zones given the difficulty of touching every square cm on a field site; (v) the best visual indicator that bentonite down-slope bentonite erosion is likely to have occurred is an accumulation of bentonite on the surface of the GCL (streaks) and at the base of the slope, however at QUELTS II there were some cases where some streak and bentonite was observed at the base but no erosion holes were identified during 28 months of inspection. The absence of any bentonite accumulation is a good indicator that there has not been any significant down-slope bentonite erosion. No significant bentonite loss was observed from the supplemental bentonite used at QUELTS I. There was some loss of bentonite from the extra powdered bentonite in the cover geotextile of GCL5 and GCL6 that was not related to any significant erosion of bentonite from the core (i.e., between the GCL cover and carrier geotextiles) or from between the GCLs at the overlap. Welds down-slope but especially cross-slope welds (as would occur in areas where a sample had been taken for destructive testing and a patch had been welded into place) were notable locations for initiation of down-slope erosion features. It follows that if destructive tests are to be conducted on welds then, once the repair is completed and tested, the liner should be covered immediately and not left exposed.

In the field, the time required for sufficient bentonite erosion to prevent self-healing and hence a significant reduction in the hydraulic containment provided by the GCL will depend on many factors that affect the uptake and loss of moisture from the GCL including: the type of GCL, the particle size distribution and initial moisture content of the subsoil below the GCL, the solar radiation received by the geomembrane (which will depend on site latitude, slope angle, orientation of the slope with respect to the sun, weather conditions etc.) and hence thermal cycles experienced by the GCL.

Covering the geomembrane in a timely manner, as recommended by reputable GCL manufacturers, eliminated the issue of down-slope bentonite erosion and panel shrinkage and this should be adopted. If the liner cannot be covered in a timely manner then GCLs can be selected that appear to eliminate down-slope erosion, although consideration would still need to be given to potential panel shrinkage. Unfortunately, GCLs most prone to down-slope erosion are the commonly used GCLs that are either (i) least likely to experience panel shrinkage, and/or (ii) can be easily heat-tacked to minimize the risk of shrinkage. These GCLs can still be used (and may be very cost effective) but they must be covered in a timely manner as recommended by the manufacturers. GCLs with a lower likelihood of down-slope erosion (e.g., polymer coated GCLs with the polymer coating facing up to minimise moisture loss) will require overlaps of 300 mm (or possibly more under some conditions).

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