Wrinkling of a Geomembrane on a Compacted Clay Liner on a Slope

R. Kerry Rowe[1*], P. Yang[2], M.J. Chappel[3], R.W.I. Brachman[4],W.A. Take[4]

[1]*Professor, Killam Fellow and Canada Research Chair in Geotechnical and Geoenvironmental Engineering, GeoEngineering Centre at Queen's-RMC, Queen's University, Ellis Hall, Kingston ON, Canada K7L 3N6.*

[2]*Associate Professor,Key Laboratory of Geotechnical and Underground Engineering of Ministry of Education, Tongji University, Shanghai, People's Republic of China, 200092.*

[3] *Graduate Student, GeoEngineering Centre at Queen's-RMC, Queen's University, Kingston ON, Canada, K7L 3N6.*

[4] *Associate Professor, GeoEngineering Centre at Queen's-RMC, Queen's University, Kingston ON, Canada, K7L 3N6*

E-mail: kerry@civil.queensu.ca

ABSTRACT: The development of wrinkles in a 1.5 mm thick textured HDPE geomembraneover a compacted clay liner on a 3H:1V (33%; 18°) slope is reported at different times of the day on 25 August 2008. The width of wrinkles did not vary significantly throughout the day once notable wrinkling had developed. The mean wrinkle width (0.31 m) is greater than that at other sites with a GCL below the geomembranereported in the literature (0.21-0.23m). The maximum connected wrinkle ranged from less than 20 m at 08:40 to 1370 m at 15:10. Given the size of the area monitored(0.26 ha) one might expect about four such wrinkles per hectare. Wrinkles covered less than 2% of the area at 08:40 but exceeded 8% after 10:10 with a maximum of 20% at 15:10. The practical implications of the time of day the geomembrane is covered and the effect this could have on leakage are discussed.

Key words: geomembranes, wrinkles, landfills, liners, leakage

1. INTRODUCTION

It is well known that when a constrained high density polyethylene (HDPE) geomembrane is exposed to solar radiation, wrinkles (also called waves) develop in the geomembrane (Giroud and Morel 1992;Giroud 1995;Giroud 2005; Rowe 1998, 2005).Prior to 2005, publications relating to wrinkles in HDPE geomembranes at a number of specific sites had indicated that: (i) an increase in geomembranetemperature to 50°C could create a0.1 mhigh wrinkle (Giroud and Peggs 1990), (ii)larger wrinkles (0.05 - 0.1 m high and 0.2 - 0.3 m wide) could develop parallel to the roll length and smaller (less than 0.05 m high and 0.2 m wide) wrinkles developed perpendicular to the seams for a 1.5 mmgeomembrane (Pelte*et al.* 1994), (iii)wrinkle heights of between 0.05 - 0.13 m and widths of 0.1 - 0.8 mformed in a2 mm thick HDPE (Touze-Foltz *et al.* 2001), and (iv) individual wrinkle lengths of between 17 m and possibly 40 m could develop in a relatively small (0.063 ha) cell(Rowe *et al.* 2004). Rowe et al. (2004) suggested that it was not just individual wrinkle length but rather the hydraulically connected length of a distribution of wrinkles that would control the leakage through a composite liner.

The potential practical significance of connectedwrinklelength with respect to leakage was demonstrated by Rowe (2005) who showed that wrinkles could explain the difference between the observed leakage through primary liners in double lined landfills (Bonaparte *et al.* 2002) and what would be expected if the geomembrane was in direct contact with the underlying clay liner as commonly assumed in design calculations. By back calculation using reasonable parameters, the observed leakage could be explained by onewrinkle witha hole per hectare having a length of between less thana hundred meters and about 2000 m. However, at that time, no technique had been developed for directly quantifying the connected length of a wrinkle network.

Take *et al.* (2007) developed a low-altitude aerial photogrammetric technique for quantify geomembrane wrinkles. Chappel*et al.* (2008) used this technique to quantify wrinkles in a 1.5 mm thick textured geomembrane overlying a sand foundation soil on a 140 m wide by 65 m long (0.91 ha) 3H:1V slope located at 46°10N 60°06 Won18 July 2006when the maximum ambient temperature was 28°C. It was reported that 92% of wrinkles had widths between 0.1-0.3 m with an average wrinkle width of0.21 m (standard deviation = 0.06 m). Chappel*et al.* (2012) then used the technique to quantify wrinkles in a 1.5mm smooth black HDPE geomembraneresting on a geosynthetic clay liner (GCL) on a 55 mby 140 m (0.77 ha)landfill base located at 44°23' N 79°43' W on 11 June 2007 when the maximum ambient temperature was 26 °C. At this site 96% of wrinkles had a width between 0.1 and 0.3 m with an average wrinkle widthof0.23 m (standard deviation = 0.03 m). The connected wrinkle length ranged from 30m at 08:45 to 2500 m at 13:45. Finally, the technique was used to examine wrinkles in a 1.5mm thick geomembrane resting on a GCL at the Queen's University Environmental Liner Test Site(QUELTS) located at 44.34°N and 76.39°W, over a 3 year period. At this site both a76 m wide by21 m long (0.16 ha) 3H:1V slope and an 76 m wide by 19.4 m long base (0.15ha) were examined. On the dates examined the maximumambient temperature was 33°C(Rowe *et al.* 2012b). At QUELTS 96% of wrinkles had a width between 0.1 and 0.3 m with an average wrinkle width of 0.22 m (standard deviation = 0.04 m) on the slope and0.20 m (standard deviation = 0.04 m) on the base. In the early morning on cold days (ambient temperatures near zero) there were essentially no wrinkles however on sunny days the longest connected wrinkle was about 1500m on the 0.15 ha base and about 2000m on the 0.17 ha slope. None of the published data noted above deals with wrinkle length and width for a textured 1.5 mmgeomembrane over a compacted clay liner on a slope and hence the effect that this may have on wrinkling is unknown.

The objective of this paper is to quantify the length of the longest hydraulic connected wrinklesthat formed in an exposed composite liner with a textured 1.5 mmgeomembrane over a compacted clay liner on a 3H:1V(33%; 18°) slope at different times of the day on 25 August 2008 and to discuss these results in the context of previous findings summarized above.

2. SITE DETAILS

This siteis located at latitude of 44°'N and longitude 78°W. The portion of the liner examined, part of the primary composite liner at the site, was constructed in August 2008. The uncovered relevant portion of the site examined was 63 m wide (approximately north to south) with a 42m long on a3 horizontal to 1 vertical (3H:1V) slope, sloping down to the west (Figure 1). A textured black, 1.5 mm thick, high density polyethylene (HDPE)geomembrane was installed over a compacted clay liner from the anchor trench at the top of the slope (east), with the roll running down the slope. The geomembrane was seamed with dual hot wedge thermal fusion, and quality control tests were performed throughout installation. In addition to the anchor trench to the east (top of slope) the geomembrane was constrained by sandbags at the north and south edges and at the bottom of slope (west).

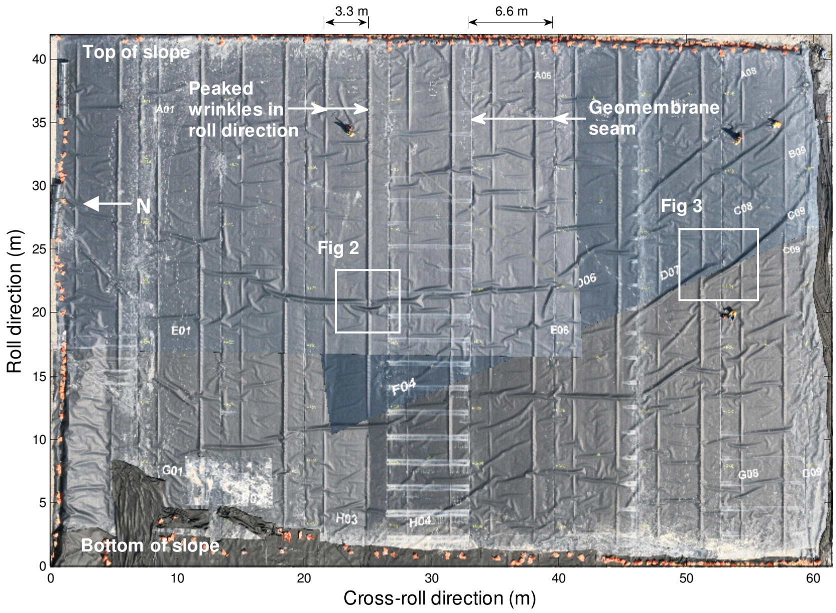

Figure 1 Image of the entire landfill slope at 15:10

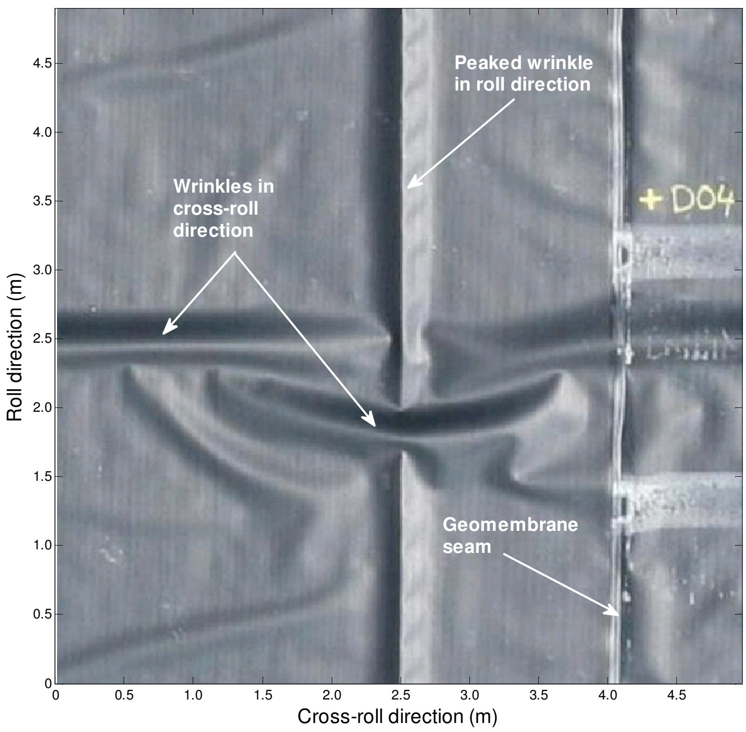

Figure 2 Roll direction and cross-roll direction wrinkles

3. METHOD

A low altitude aerial photogrammetry system was used to capture images of the geomembrane for quantification as described by Chappel et al. (2007). Before photos were taken, a grid of ground control pointswas painted on the geomembrane and surveyed. A digital single lens reflex (DSLR) camera was mounted under a 6.4-m-long helium-filled blimp. The blimp was flown over the site at a height of about 60 m and photos were taken at six times between 08:40 and 15:10. Once the photographs had been taken, the grid of ground control points was used to transform the individual images to obtain a constant scale of 10 mm to one pixel (Take et al. 2007). A single master image of the entire slope was then created by stitching the transformed images together using the global coordinates of the markers (Figure 1). The pixels in the digital master image that correspond to geomembrane wrinkles were chosen and highlighted, and the widths and lengths of the wrinkles as well as the connectedness of wrinkles was digitally quantified asdescribed by Take *et al.* (2007). For the purposes of assessing what represented a wrinkle, a threshold of 0.03 m was set. Wrinkles with an assessed height less than this were not considered. Thus the reported number, length and area covered by wrinkles may be underestimated.

4. RESULTS

The composite liner examinedin this paper ran 42m down the slope (y-axis) and 63 m across the slope (x-axis) giving a total unrestrained area of 0.26 ha (Figure 1). The geomembrane was manufactured using the blown film process, where the geomembrane was drawn out of a circular die and then cut, folded, and unfolded during the cooling process before it was rolled. The folding introduced two creases located about 1.6 – 1.7 m from each edge of the roll and about 3.3m apart. When the geomembranecomes off the roll, these creases are almost unnoticeable. However after the 6.6-m-wide geomembrane panels were welded (Figure 1), and restrained by the anchor trenchat the top of the slope and sand bags elsewhere (the dots around the edges of the geomembrane shown in Figure 1 are sand bags), these creases became loci where wrinkles tended to develop when the geomembranewas heated to a temperature higher than the as-installed temperature by solar radiation. At these locations the wrinkles had a "peaked" or inverted "V" like shape (Figures 1, 2 and 3) and ran down the slope in the roll directionat a spacing of about 3.3 m; they are referred to as "peaked wrinkles" (Figures 1, 2 and 3). Based on the first authorsexperience at sites where the geomembrane was produced using a flat die (which has no creases), wrinkles would still have developed in the down-slope (roll) even if these creases had not been present.

Although the peaked wrinkles in the roll direction are of note, they are not the only wrinkles that form. Wrinkles also formed across the slope and, in many cases, connected to the peaked wrinkles (Figures 1 and 2). Thus even though there was no obvious point of initiation for cross roll wrinkles, they still formed. A third set of wrinkles were included at an angle of about 45^o to the roll (down-slope) direction (Figures 1 and 3); some of these wrinkles may have been related to small construction wrinkles in the geomembrane at the time the geomembrane was placed.

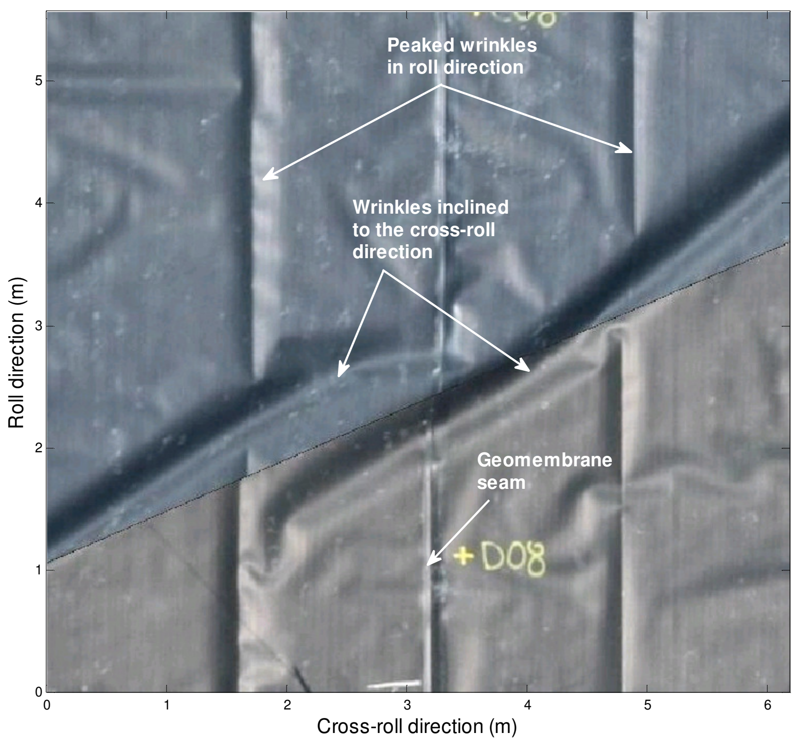

Figure 3 Close up of geomembrane showingpeaked wrinkles in the roll direction down slope and inclined wrinkles running across the slope

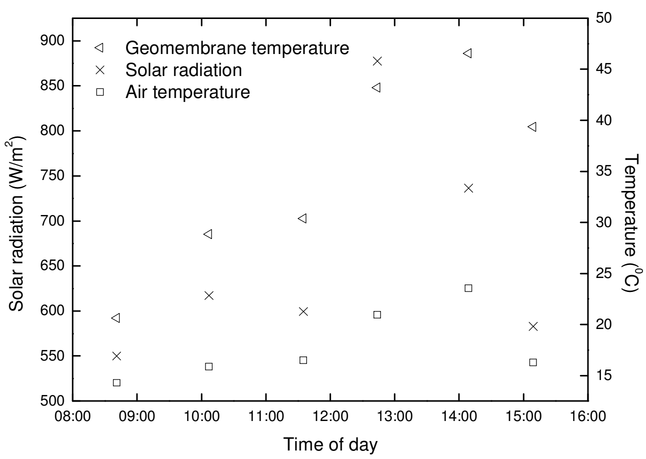

Figure 4 Solar radiation, air and geomembrane temperature versus time of day

At the times in the day that the geomembrane was photographed the ambient temperature (Figure 4) ranged between about 14^{o}C at 08:40 and a maximum of 24^{o}C at 14:10. Thus this was a pleasant but not especially hot day.The solar radiation experienced by the geomembraneis very sensitive to both the time of day (reaching a maximum around noon) and also to cloud cover which can vary substantially even over a relatively short period of time. As a result of these factors, the solar radiation at the times monitored (Figure 4) did not follow the pattern of monotonically increasing to a maximum around noon and then monotonically decreasing in the afternoon as would be expected on a cloudless sunny day. Nevertheless there was an effect of time of day and at the times monitored, the solar radiation ranged from a low of 550 W/m^2 at 08:40 to a maximum 880 W/m^2 at 12:45 and down to 580 W/m^2 at 15:10. Also on a slope the actual geomembrane exposure to the solar radiation depends on the slope orientation. In this case the slope facing west-north-west experienced the most direct sun exposure in the afternoon. The black geomembraneabsorbedradiation from the sun and as a consequence its temperature was greater than ambient temperature throughout the day (Figure 4). At 08:40 the geomembrane temperature of 21^{o}C was 7^{o}C above ambient temperature. At 12:45, 14:10 and 15:10 the geomembrane temperature was about 23^{o}C above ambient with the maximum measured geomembrane temperature being 47^{o}C at 14:10. Since the geomembraneis laterally restrained butneeds to expand when heated, wrinkles will form and it can be anticipated that the time of day and geomembrane temperature will have some effect on wrinkling as discussed below.

4.1 Wrinkle width

The mean and standard deviation of the wrinkle widths (Figure 5a) were fairly consistent throughout the day. Except for 08:40 when there were very few wrinkles and these were mostly related to construction, the mean wrinkle width was 0.3 -0.32 mwith a standard deviation of 0.05 - 0.07m. Thus at any time when there were a large number of wrinkles, the time of day had relatively little effect on wrinkle width. The wrinkle widths at all of the times monitored appeared to be normally distributed with a mean of 0.31 m and standard deviation of 0.06m (Figure 5b). The widths ranged from 0.03 m to 0.58m. Unlike the other sites discussed earlier, where more than 90% of wrinkle widths were between 0.1 m and 0.3m, at this site only 40% fell in this range but about 90% of widths were between 0.2 m and 0.4 m.

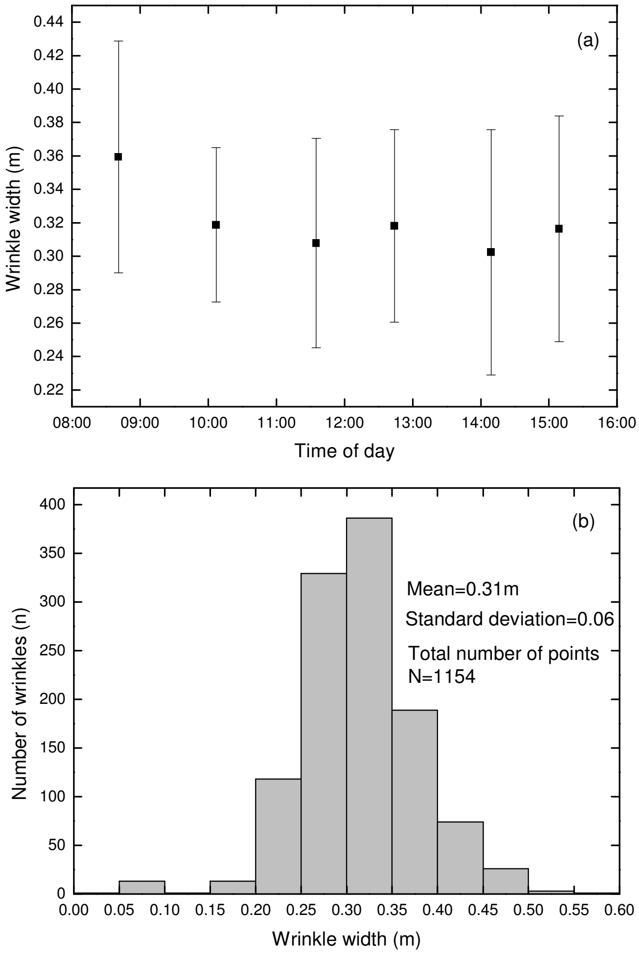

Figure 5 Wrinkle width: (a) mean plus or minus one standard deviation at different times of day, (b) histogram of all data

The average width of 0.31 m on the slopeat this site was notably larger than observed on the slope (0.21 - 0.22 m) or base (0.21 – 0.23 m) at the sites described earlier. The reason for this difference is not known with certainty, however this site was the only one where the geomembranewas placed overa compacted clay liner and the difference may be a consequence of this difference in material below thegeomembrane; more dataat other times on this site and at other sites with a geomembrane over compacted clay would be required to confirm this hypothesis.

4.2 Effect of time of day on number of wrinkles and area covered by wrinkles

The wrinkles and the related changes in solar radiation and geomembrane temperature varied substantially with the time of day. All of the significant wrinkles (i.e., with a height greater than 0.03 m) are shown at six times over the day in Figure 6. Both the gray and black lines shown are tracings of wrinkles, with the grey wrinkles forming the longest connected wrinkle network at that time.

At 08:40 the solar radiation (550 W/m^2) had only started to heat the geomembrane (T=21°C) and in total there were less than 20 wrinkles (Figures 6a and 7) with less than 2% of the slope area being wrinkled (Figure 8). At this time, none of the wrinkles were peaked roll direction wrinkles; rather they were mostly inclined wrinkles with some cross roll wrinkles. This demonstrates that local irregularities at the site and initial slack in the geomembrane at the time of placement can be the initial loci for wrinkle formation unrelated to any creases in the geomembrane. At 10:10 and 11:35 on this particular day the solar radiation (620 W/m^2 and 600 W/m^2) and geomembrane temperatures (29°C and 30°C) were similar resulting in about 150 and 130 wrinkles respectively and about 8% of the slope being covered by wrinkles. At these times, the peaked wrinkles had appeared and represented a significant proportion of the total number of wrinkles (Figure 6b and 6c).

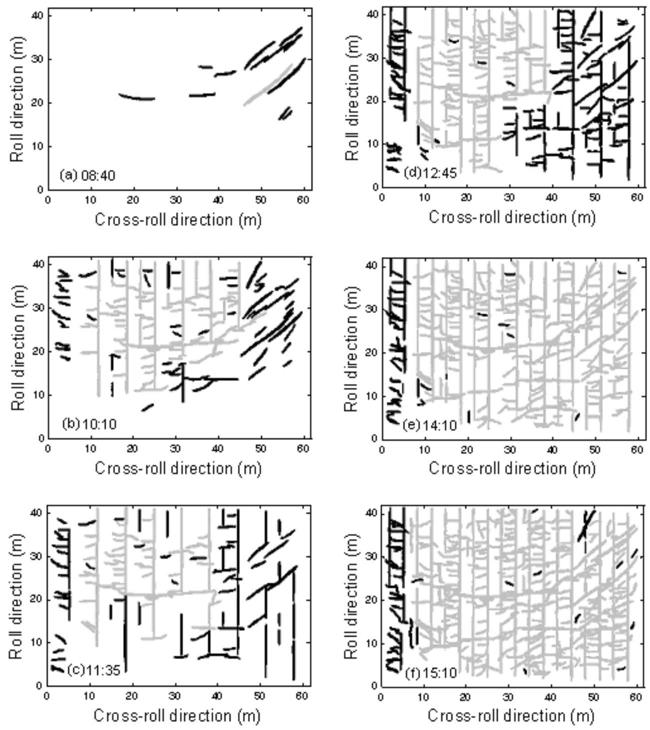

Figure 6 Significant wrinkles for the entire slope portion of the landfill highlighting the longest interconnected wrinkle features in grey at 08:40, 10:10, 11:35, 12:45, 14:10 and 15:10

At 12:45 and 14:10 the solar radiation (880 W/m^2 and 740 W/m^2) had increased the geomembrane temperatures to 43°C and 47°C giving rise to about 240 and 280 wrinkles respectively with 13% and 16% of the slope being covered by wrinkles. By 15:10 the solar radiation measured by thepyranometer (580 W/m^2) and geomembrane temperatures (39°C) had begun to decrease however the geomembrane (and presumable underlying compacted clay liner) were still hot and, since the slope is west-facing, the actual radiation impacting the slope in the afternoon may have been greater than measured by the pyranometer. The relative importance of these two factors is unknown, but it is known that the number of wrinkles (about 350) and proportion of the slope that was wrinkled (20%) were at a maximum at this time (Figures 7 and 8). This may be expected to have an impact on the connected length of wrinkles to be discussed in the next section.

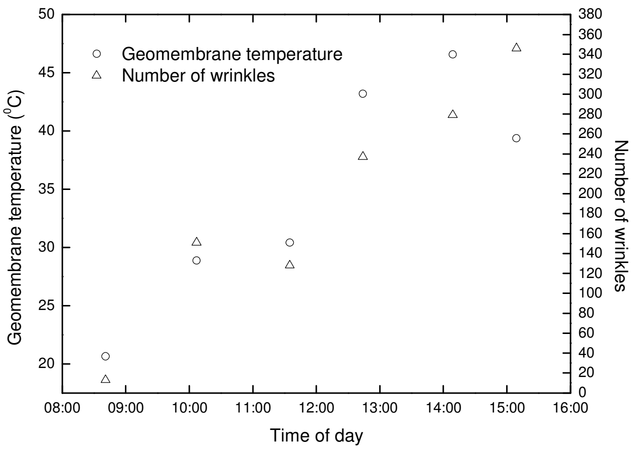

Figure 7 Geomembrane temperature and number of wrinkles versus time of day

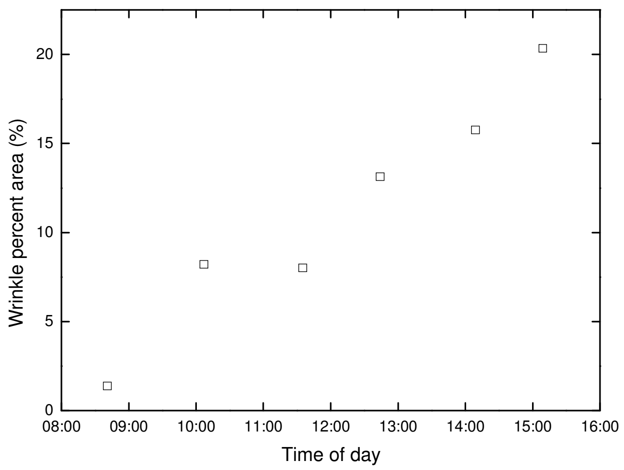

Figure 8 Variation in percentage of slope area with wrinkles versus time of day

4.3 Connected wrinkle length

A hole in the geomembrane at the location of any wrinkle will substantially increase the leakage compared to a hole in the geomembranein direct contact with the clay liner (Rowe 1998, 2005, 2012). The simplest of the analytical solutions presented by Rowe (1998) considers the case where there is no interaction between wrinkles. For this case the leakage through composite liner is given by:

$$Q = 2\,L\,[kb + (kD\,\theta)^{0.5}]\;h_d\,/\,D \qquad (1)$$

where Q is the leakage [m^3/s], L is the length of the wrinkle with a hole [m]; $2b$ is the width of the wrinkle [m]; k is the hydraulic conductivity of the clay liner [m/s]; θ is the transmissivity of the geomembrane-clay liner interface [m^2/s];h_d is the head loss across the composite liner [m]; and D is the thickness of the clay liner [m]. Of these parameters, those related to wrinkles are the length$L$ and width $2b$. Based on the presently available data, the average wrinkle width, $2b$, is between about 0.2 m and 0.3 m (depending on the site) prior to covering and tends to be relatively constant throughout the day provided that there are a reasonable number of wrinkles present as discussed above. The primary unknown is the length of the wrinkle that may have a hole.

As the geomembrane temperature increases, the number of wrinkles (Figure 7) and the area of the liner with wrinkles (Figure 8) both generally increase. An increase in number of wrinkles and area covered by wrinkles both increase the probability that a hole and a wrinkle will coincide. If the wrinkle with a hole had a length, L, less than 20 m as at 08:40 (Figures 6a and 7), calculations using typical parameters (Table 1) show that the leakage is very small (Q< 20 lphd). For a municipal soil waste landfill, this leakage (advection) is of no practical significance since the corresponding Darcy flux is less than 1 mm per year (v_a = 0.0007 m^3/m^2/a, Table 1) and the contaminant impact for volatile organic compounds would be controlled by diffusion through the geomembrane (see Rowe et al. 2004). However, the maximum connected wrinkle length (shown in grey in Figure 6) can vary greatly throughout the day (Figure 9).

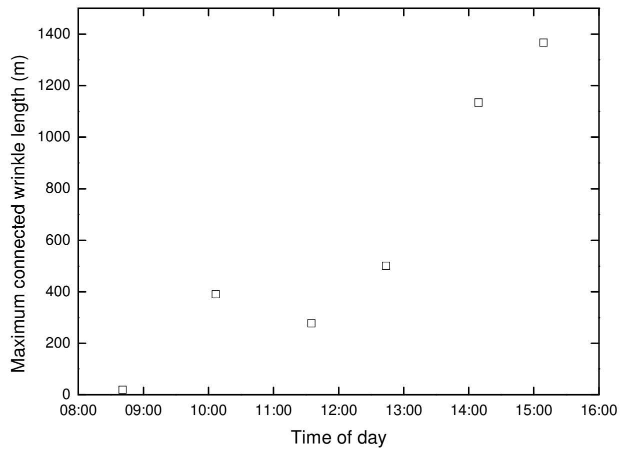

Figure 9 Variation in maximum connected wrinkle length with the time of day

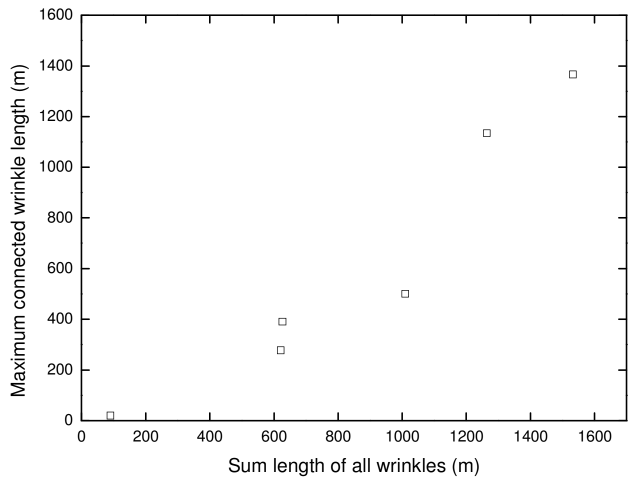

Figure 10 Relationship between maximum connected wrinkle length and the sum of the length of all wrinkles

As the geomembrane temperature increased so too did the number of wrinkles (Figure 7) and, therefore, the sum of the length of the wrinkles. More significantly, the connection between wrinkles increased because the roll direction wrinkles connected with the cross-roll and inclined wrinkles to form networks of hydraulically connected wrinkles (Figure 6). At 08:40 the sum of the wrinkle lengths was just less than 100 m, but the maximum connected wrinkle length was less than 20 m (Figure 10) as noted above. By 10:10 the sum of the wrinkle lengths and the area covered by wrinkles had increased six fold to 630 m and 8% respectively however the maximum connected wrinkle length (shown in grey in Figure 6b) had increased 20 times to about 400 m (Figure 10).

The average solar radiation and geomembrane temperature at 10:10 and 11:35 were very similar: 620 and 600 W/m^2 and 29 and 30 °C as was the area covered by wrinkles (8%). However, the conditions were close to the threshold where a small change in a few wrinkles can make a large difference as to whether, for example, two connected wrinkles join to form one much large connected wrinkle. Thus while there were many similarities in the wrinkling in these cases (Figure 6b and 6c), there was a significant difference in the maximum connected wrinkle length with it being about 400 m at 10:10 and 280 m at 11:35 (Figure 9).

Table 1 Calculated leakage, Q, and corresponding Darcy flux, v_a, for a composite primary liner with a compacted clay liner over a leak detection system assuming one hole in a wrinkle of length L per hectare (rounded to two significant figures)

Wrinkle length with hole, L (m)	Leakage, Q (lphd)	Darcy Flux, v_a ($m^3/m^2/a$)
20	19	0.0007
100	93	0.0034
280	260	0.0095
500	470	0.017
1130	1050	0.039
1370	1280	0.047

Assumptions: Compacted clay liner hydraulic conductivity, k = 1x10^{-9} m/s; wrinkle width, 2b = 0.3 m; liner thickness D = 0.6 m; transmissivity, θ = 2x10^{-8} m^2/s; head drop across liner, h_d = 0.9 m

The sensitivity of the maximum connected wrinkle length to small variations in a few wrinkles that may or may not connect adjacent smaller wrinkle networks is also illustrated by comparing the results at 12:45 and 14:10 in Figures 6d and 6e. At 12:45 there werean extensive number of wrinkles (240; Figure 7) and sum of the lengths of the wrinkles was 1000m (Figure 10), however the maximum connected wrinkle length was only about 500 m. At 14:10 the geomembrane temperature was only slightly higher than at 12:45 (46^{o}C versus43°C) but by 14:10 the different wrinkle networks had mostly coalesced (the exception being the wrinkle network in the northern most panel of geomembrane) and although there was only a 26% increase in the sum of all wrinkle lengths (1000 mat 12:45versus 1260 m at 14:10; Figure 10), the maximum connected wrinkle length increased by 126% (500 mat 12:45versus 1130 m at 14:10; Figure 10).

Because of the heat absorbed by the clay liner below the geomembrane and the fact it was facing west, once many wrinkles had been established, it took time for the wrinkles to reduce even though the thermal radiation andgeomembrane temperature were decreasing mid-afternoon. Thus, of all the times monitored, the maximum area (20%; Figure 8) and connected wrinkle length (1370 m; Figure 9) were observed in the mid-afternoon (15:10) when the measured solar radiation (580 W/m^2) and geomembrane temperature (39^{o}C) were lower than at 14:10.

Figure 11 shows the relationship between maximum connected wrinkle length and the percent area covered by wrinkles. Once the percent area that was wrinkled exceeded a few % (where "few" is not well defined here but was more than 2% and less than 8%) the maximum connected wrinkle length began to increase quickly and by the time 8% of the area was wrinkled the maximum connected wrinkle length in this 0.26 ha area was between 280 and 400 m and by the time 20% of the area was wrinkled the maximum connected wrinkle length had increased to almost 1400 m (Figure 11) and this wrinkle extended over almost the entire area (grey wrinkle in Figure 6f at 15:10). The practical implications of this will be discussed in the next section.

5. PRACTICAL IMPLICATIONS

If wrinkles were present at the time the geomembrane was covered and subsequently loaded by the weight of overlying material, they may experience some reduction in height and width, (Stone 1984; Soong and Koerner 1998; Gudina and Brachman 2006; Brachman and Gudina 2008; 2011; Take *et al.* 2012) but generally one would expect there to be a gap between the geomembrane and the underlying soil. If the wrinkle was intersected by a hole (or was even close to a hole) in the geomembrane, the gap between the wrinkle and an underlying compacted clay liner would allow easy fluid flow through the hole in the geomembraneand the gap between the geomembrane and the clay liner. This would substantially increase the leakage through the composite liner compared to the case where there was no wrinkle, with the magnitude of the leakage depending on the factors identified in Equation 1, with the maximum possible leakage being defined by Bernoulli's equation (Rowe 1998).

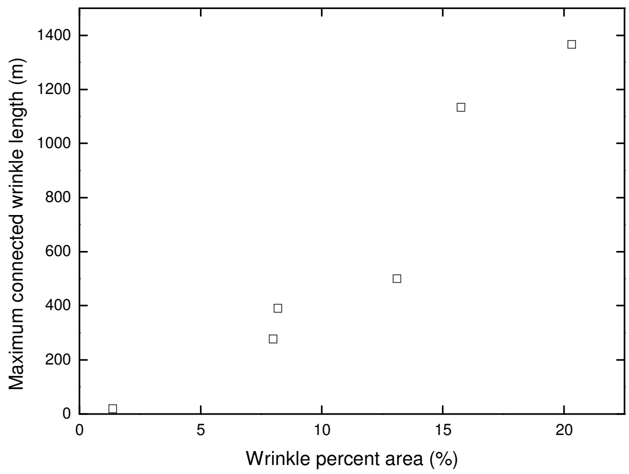

Figure 11 Relationship between the maximum connected wrinkle length and the percentage of the area of the slope with wrinkles

The effect of wrinkle length is illustrated in Table 1 for atypical compacted clay liner thickness, hydraulic conductivity, good construction and corresponding interface transmissivity (as given in Table 1), an underdrain below the liner, and a 0.3m design head on the liner.The wrinkle width was taken to be 0.3m based on the average values observed in this study. This represents a worst case and the wrinkle width could be reduced by a factor of about two if the applied pressure was about 250 kPa (based on studies cited earlier).

If the section surveyed was typical of construction elsewhere on the landfill, there would be about four such areas per hectare. This assumes the sections have been isolated by sand bags and covered at a similar time of day. Had the area been larger and not isolated by sand bags then the number of areas per hectare would have been smaller but the longest connected wrinkle much longer.Assuming the four areas are isolated, there would be four wrinkles per hectare with the maximum connected length indicated in Figure 10 for a given time of day that the geomembrane was covered. With good construction quality control and assurance, there may be 2-12 holes per hectare with a median hole area of 1cm^2 (see Rowe 2012 for a review of the data). Based on Bernoulli's equation, one such hole could allow a leakage of about 13,000 litres per hectare per day (lphd) or 0.46 m^3/m^2/a if there was no resistance due to the underlying clay liner(Rowe 2012), and hence the hydraulic resistance provided by the composite liner action will control the leakage rather than the hole size. For the purposes of the calculations in Table 1, it was assumed that the liner was covered with the drainage gravel at the time of day when various wrinkle networks shown in Figure 6 had been established (i.e. 08:40, L=20m; 11:35, L=280 m; 12:45, L=500m; 14:10, L=1130 m; and 15:10, L=1370m) and that one of the holes per hectare coincided with just one of the four longest wrinkles. The probability that one of the 2-12 holes per hectare coincides with one of the four wrinkles with the maximum connected length per hectare is relatively low at 08:10 when less than 2% of the area was wrinkled, is modest at 10:10 and 11:35 when 8% of the area was wrinkled and is high at 12:45, 14:10 and especially at 15:10, when 13%, 16% and 20% of the site was wrinkled, respectively.

Inspection of Table 1shows that if the leakage was controlled by one 20m long wrinkle per hectare, the leakage would be very small (19 lphd or 0.7 mm/a). At this leakage rate,the impact for contaminants that can readily diffuse through the geomembrane (see Rowe et al. 2004; Rowe 2005) would be controlled by diffusion through the geomembrane, not advection. If the geomembrane had been covered at11:35 when the maximum wrinkle length was 280 m, the leakage would be significant at 260 lphd (9.5 mm/a; Table 1); 12:45, when L= 500 m, the leakage would be high at 470 lphd(17 mm/a), and; 15:10, when L = 1370 m, leakage would be excessive at 1280lphd (47 mm/a). Ideally, the leakage should be kept below about 100 lphd. To achieve this objective,the geomembraneat this site would need to have been covered sometime before about 09:00. Thus the number of wrinkles present (which is related to geomembrane temperature which depends on the time of day) when the geomembrane is covered by the drainage layer may have a significant effect on the leakage through a composite liner involving a compacted clay liner.

The liner examined at this site was on a slope and hence may not be subject to a leachate head of 0.3m as assumed in design calculations above. However this does not mean that holes and wrinkles cease to be important,because, on side slopes especially, they can be a conduit for the escape of landfill gas which can contaminate groundwater as well as increase the risk of explosions. The same principles that relate to leachate migration also apply to landfill gas migration.

The results provide further evidence along with the quantitative data from Chappel et al. (2011) and Rowe et al. (2012) that suggests that any cover soil should be placed over the geomembrane either early in the day or very late in the day to avoid locking in a significant area of wrinkles and long interconnected wrinkles. This is the approach in Germany where considerable care is taken to avoid wrinkles, but is not common elsewhere in the world unless explicitly required in the tender documents.

6. CONCLUSIONS

The development of wrinkles in a 1.5 mm thick textured HDPE over a compacted clay liner on a 3H:1V (33%; 18°) slope at different times of the day on 25 August 2008 has been examined. This is the first documented case for a geomembrane over a compacted clay liner. Based on the observations presented here in it can be concluded that at this site:

1. The width of wrinkles did not vary significantly throughoutthe day once notable wrinkling had developed (i.e., between 10:10 and 15:10). The mean wrinkle width was 0.31 m with a standard deviation of 0.06 m. About 90% of wrinkles were between 0.2 and 0.4m. The mean wrinkle width of0.31 m was greater than has been observed for geomembranes at other sites where the geomembrane was not underlain by a compacted clay liner (where the mean width was 0.21-0.23m). It is presently not known if this is coincidence or a function of the nature of the material below the geomembrane.

2. The maximum connectedwrinkle length was less than 20 m at 08:40 but for the rest of the day exceeded 280 m with the maximumlength being 1370 m at 15:10. Given the size of the area monitored, one would expect about four such wrinkles per hectare.

3. The area of the geomembrane that was wrinkled increased from less than 2% at 08:40 to 8% by 10:10 with a maximum of 20% at 15:10. Thus the probability of a hole coinciding with a wrinkle is low before 09:00 but modest to high over the rest of the day at the times examined.

4. Based on typical leakage calculations and assuming a leachate head of 0.3 m, on a day such as that examined, the liner should be covered before about 09:00 to keep the potential leakage to a reasonable value.

Based on the findings at this site, it appears that careful attention needs to be paid to the amount of wrinkling (and hence the time of day) when thegeomembrane is covered to ensure that the full value of installing a composite liner is realized.

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